

Sea level and ocean circulation in the ice-covered polar oceans from satellite radar altimetry

Tom Armitage
Supervisor: Ron Kwok
Radar Science and Engineering

Talk outline

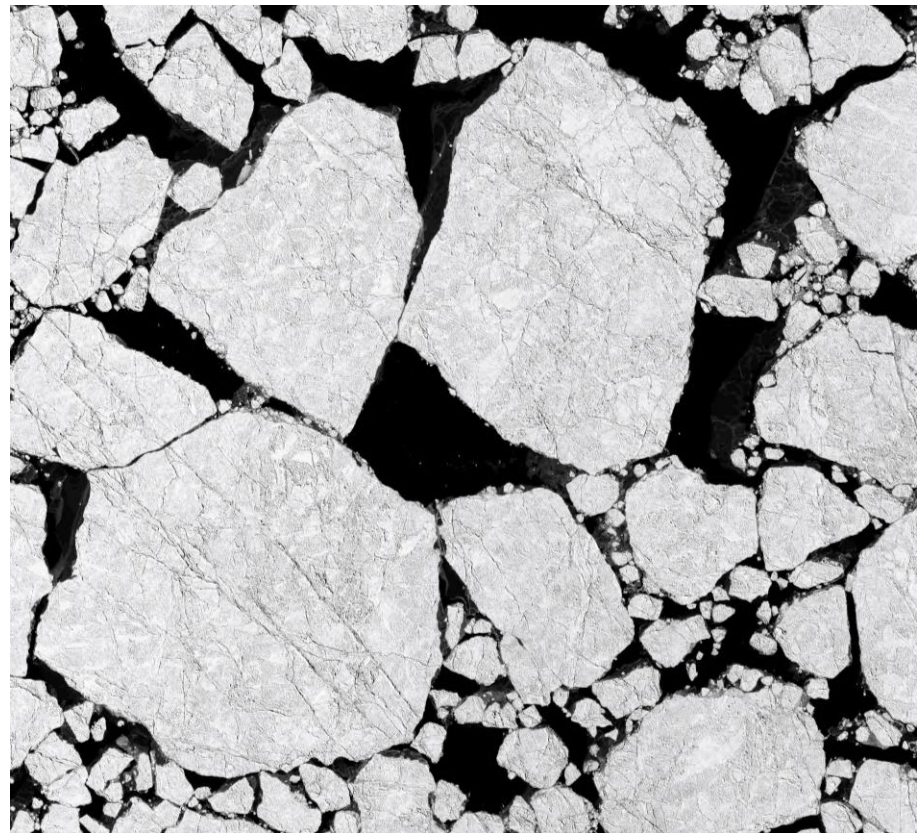
1. Why study sea level/circulation of the polar oceans?
2. Radar altimetry in the ice-covered oceans
3. The Arctic Ocean
 - Seasonal to decadal freshwater fluxes
 - Climate variability (Arctic Oscillation)
 - Changing energetics/momentum flux in the western Arctic
4. The Southern Ocean
 - Antarctic Slope Current seasonal variability
 - Ross/Weddell Gyres variability
 - Climate variability (Southern Annular Mode/El Niño Southern Oscillation)
5. Future work and future missions

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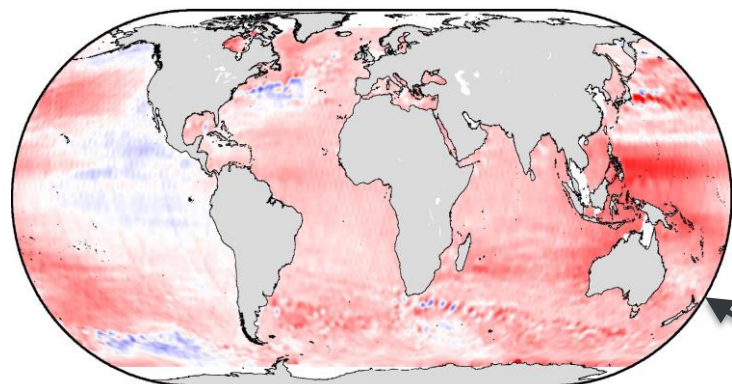
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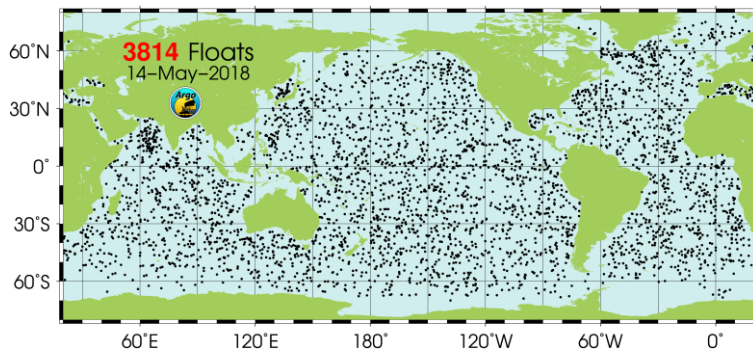
- The polar oceans are small but essential for understanding climate change
- Arctic region is experiencing rapid climate change
 - Arctic sea ice loss
 - ‘Arctic amplification’
- Southern Ocean is a climatically important region
 - water mass modification, surface fluxes, sea ice formation, glacial input
 - Driving Antarctic ice sheet melt



1. Why study sea level/circulation of the polar oceans?



- Sea level an important indicator of global climate change
 - Reflects a host of processes and acts as a ‘bulk’ measure of ocean column properties
- **But**: it is poorly measured in the polar oceans due to
 - Conventional altimetry does not cover the polar oceans or fails due to sea ice
 - *In situ* data (tide gauges, ARGO, etc.) more difficult due to harsh conditions/expense



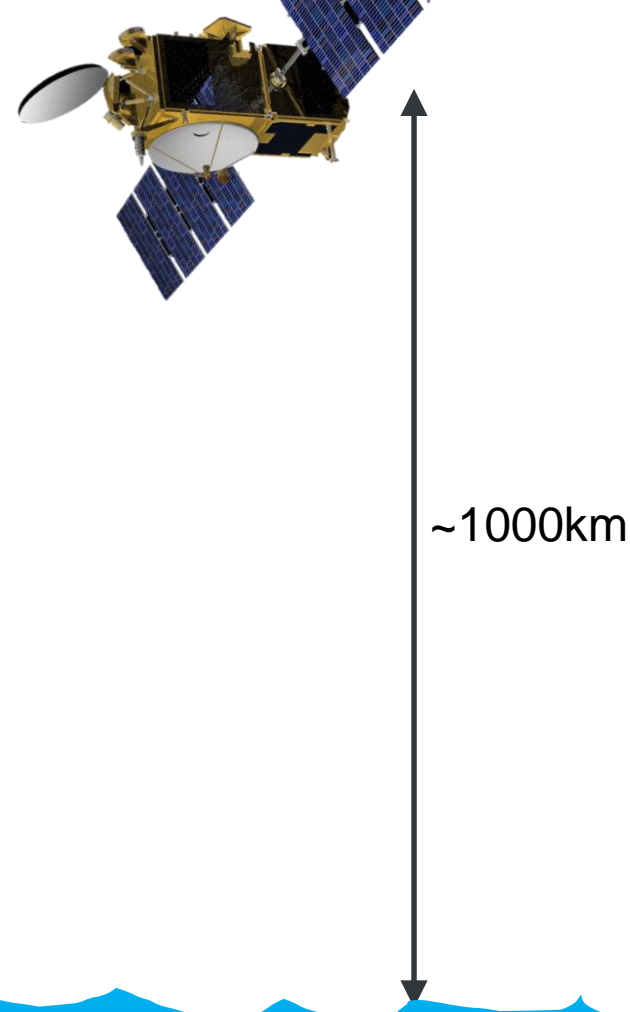
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2. Radar altimetry in the polar oceans

Conventional altimetry

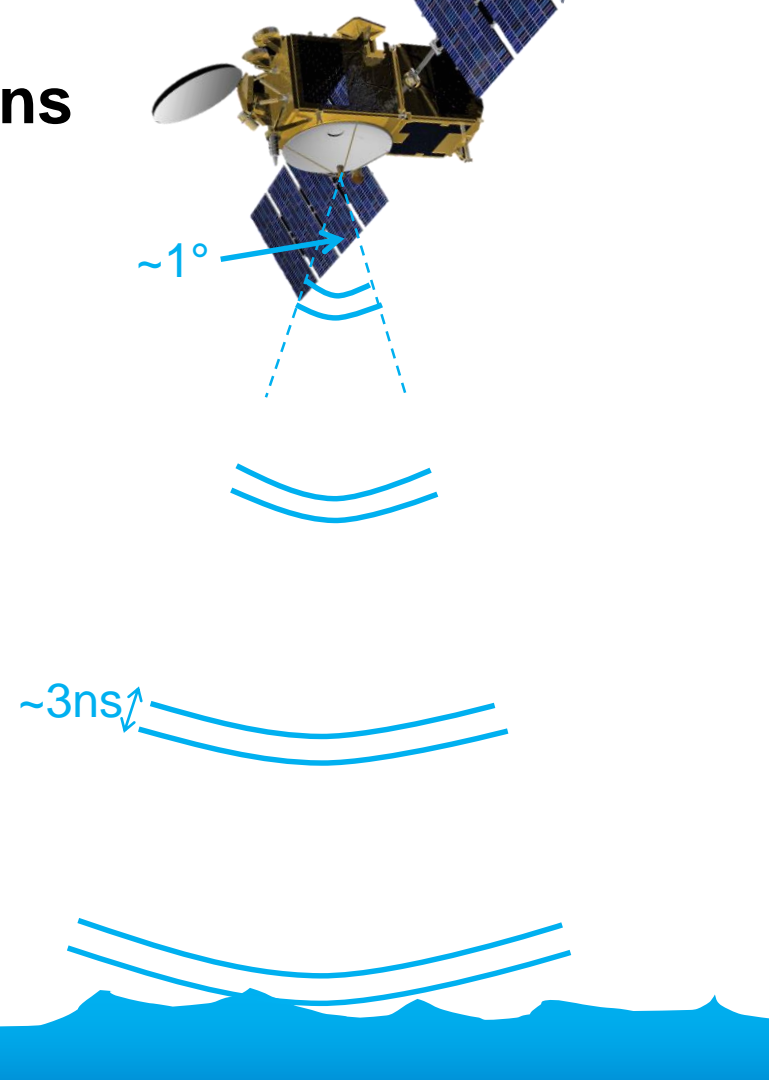
- Satellite orbiting at $\sim 1000\text{km}$



2. Radar altimetry in the polar oceans

Conventional altimetry

- Satellite orbiting at $\sim 1000\text{km}$
- Emit radar pulses to surface

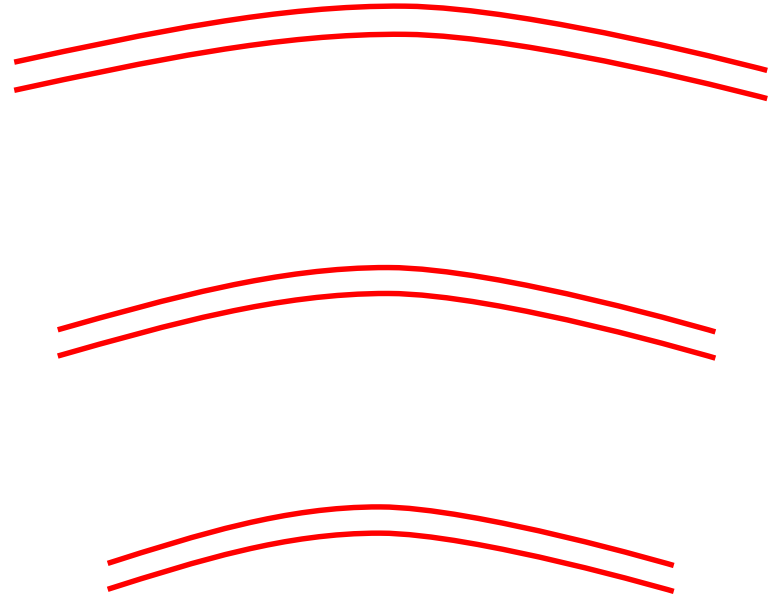


2. Radar altimetry in the polar oceans



Conventional altimetry

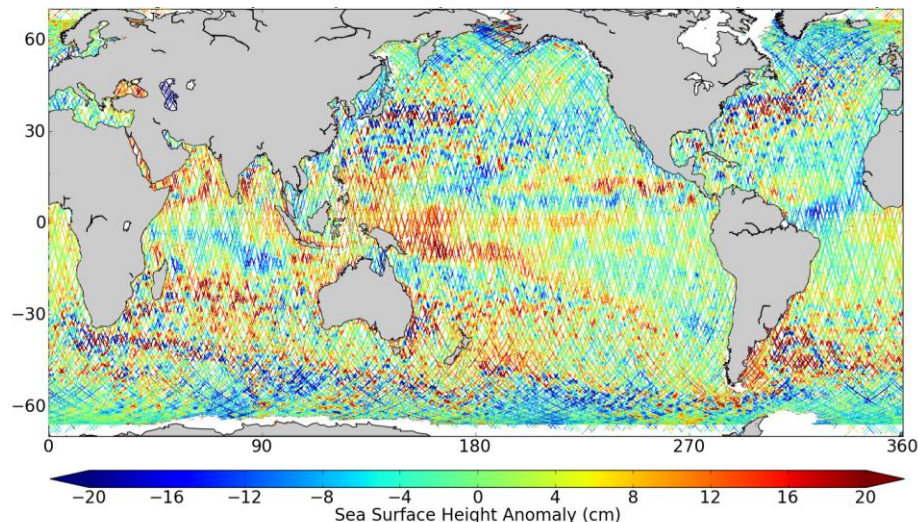
- Satellite orbiting at $\sim 1000\text{km}$
- Emit radar pulses to surface
- Receive the reflected pulses and estimate the two-way travel time, convert to range



2. Radar altimetry in the polar oceans

Conventional altimetry

- Satellite orbiting at $\sim 1000\text{km}$
 - Emit radar pulses to surface
 - Receive the reflected pulses and estimate the two-way travel time, convert to range
 - Combine this with:
 - Satellite altitude
 - Geophysical corrections
- Get sea surface height



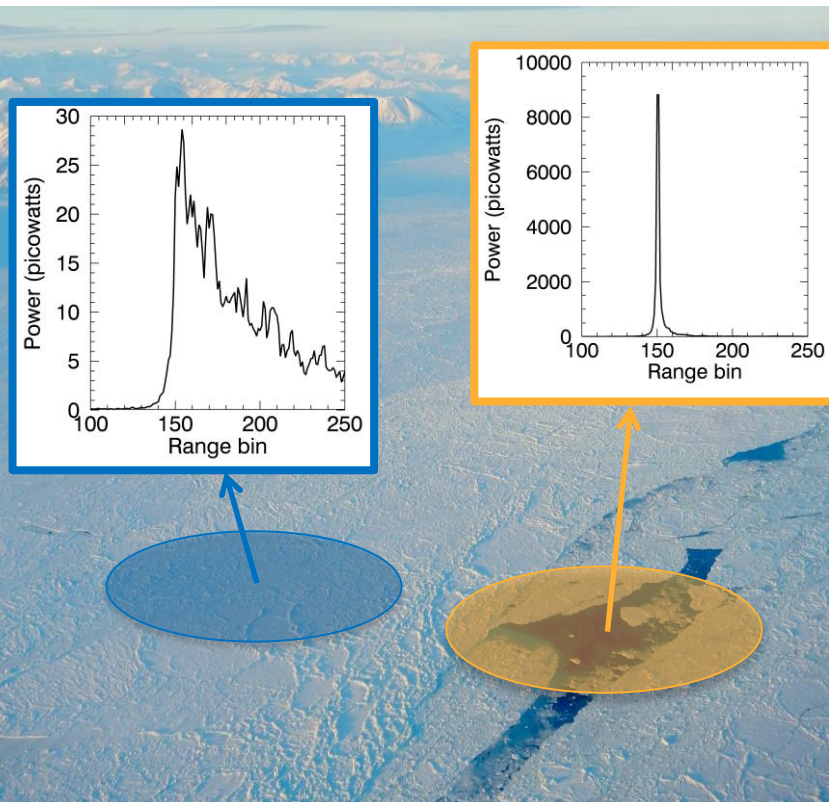
JPL 10-day along-track sea level anomaly composite
for May 4th to 14th (sealevel.jpl.nasa.gov)

2. Radar altimetry in the polar oceans



- Open ocean has well-known radar scattering properties
 - Homogeneously rough
 - Known decorrelation scales
- Sea ice scattering is highly *inhomogeneous*
 - Leads appear very bright (specular; mirror-like)
 - Deformation features

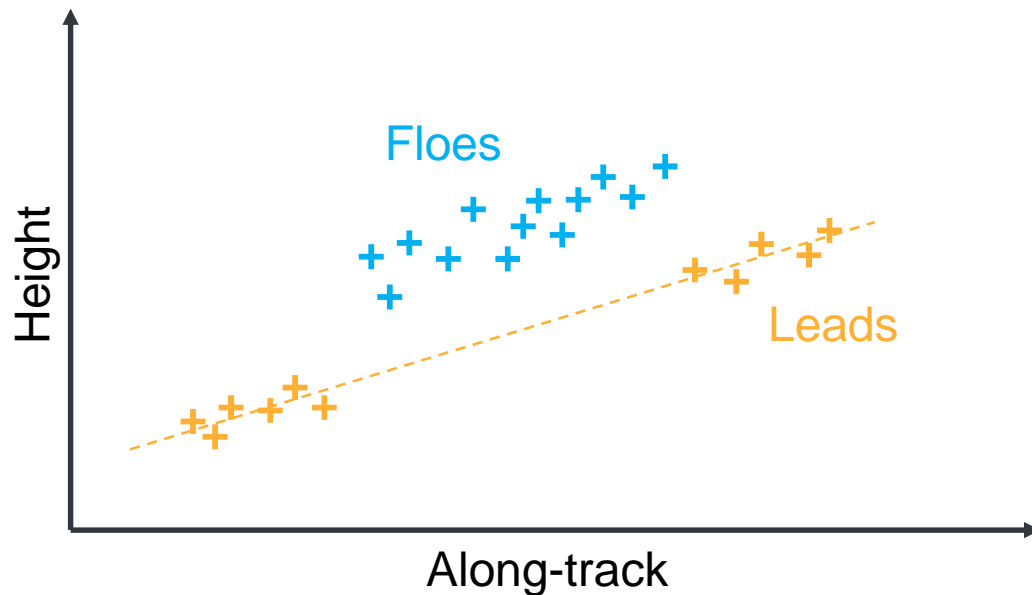
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 - Leads (cracks) appear very bright (specular; mirror-like)
 - Deformation features
- Different scattering properties allows to distinguish between surface types

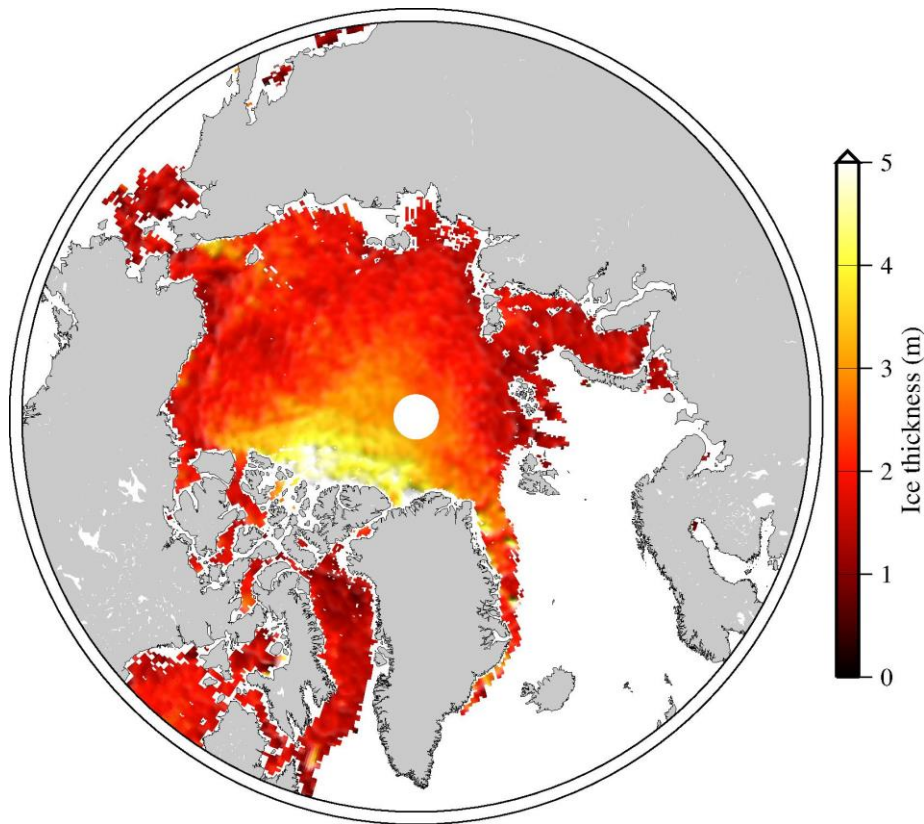
2. Radar altimetry in the polar oceans

- Measure sea level from leads
- Interpolate underneath ice floes
- Estimate sea ice freeboard/thickness

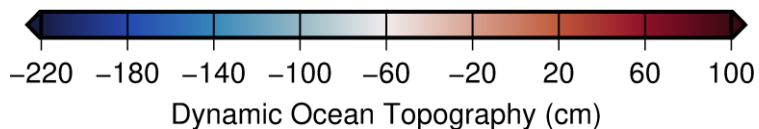
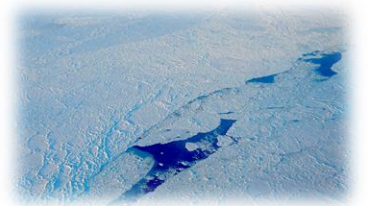
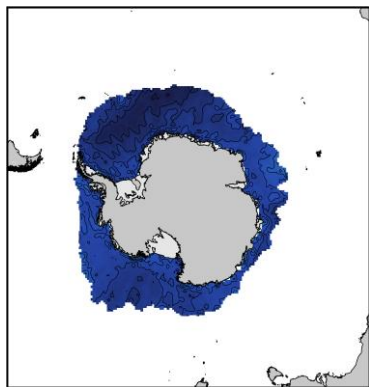


2. Radar altimetry in the polar oceans

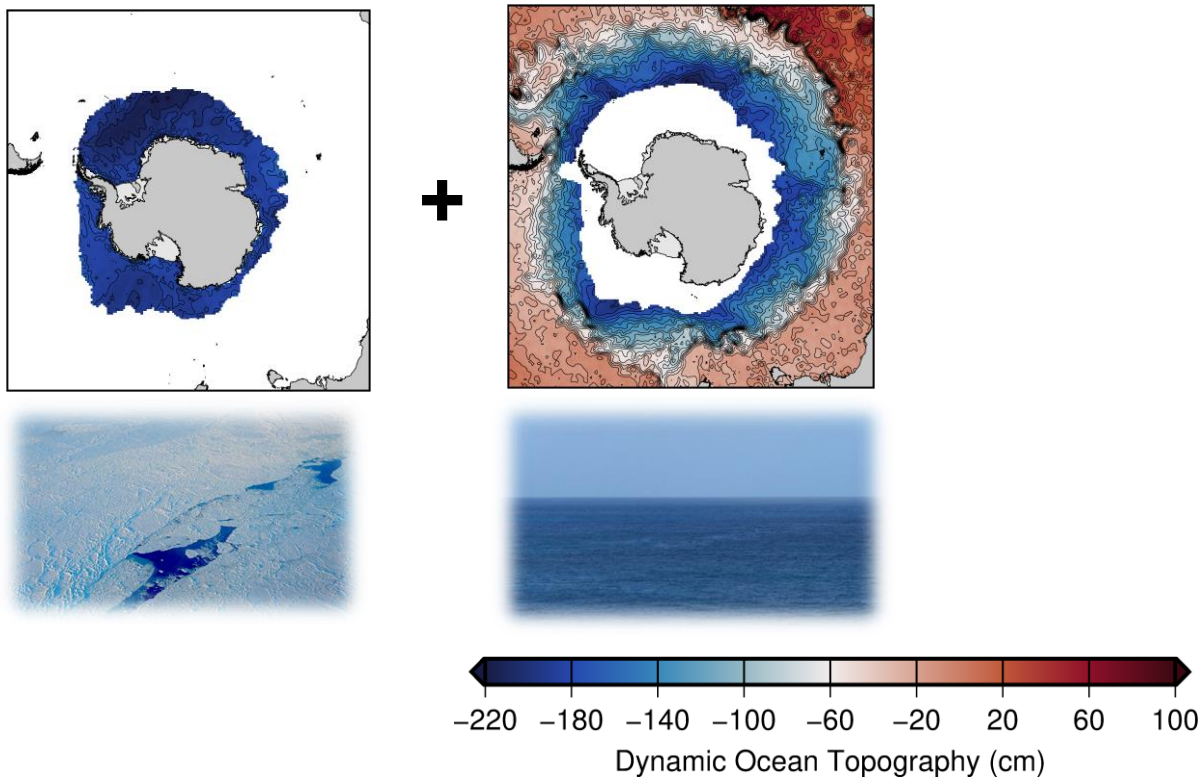
- Measure sea level from leads
- Interpolate underneath ice floes
- Estimate sea ice freeboard/thickness
- Sea level is a by-product of processing to get sea ice thickness



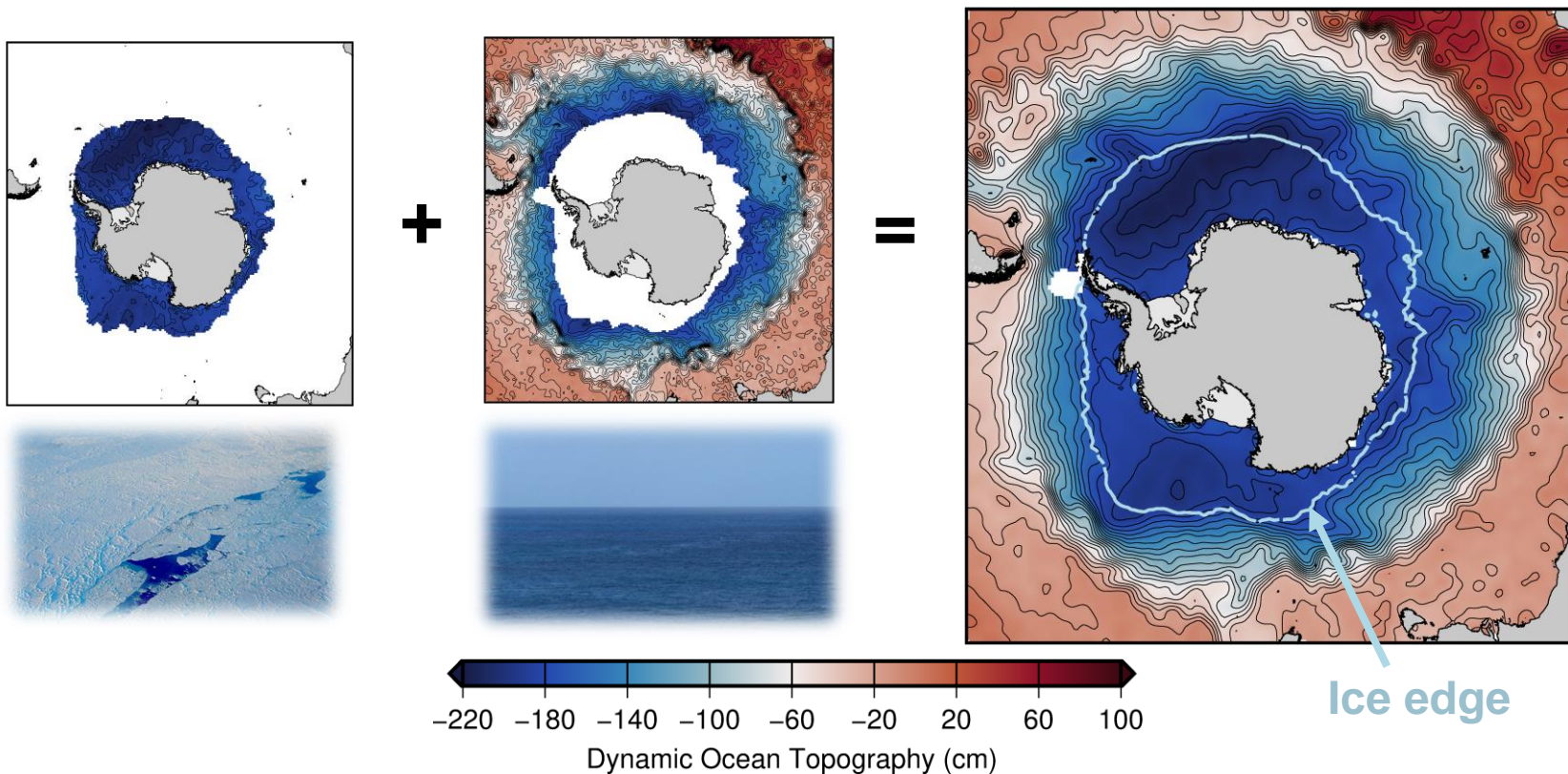
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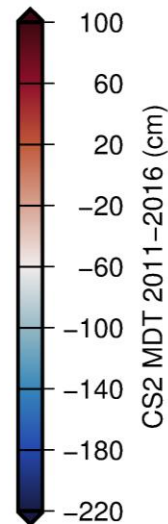
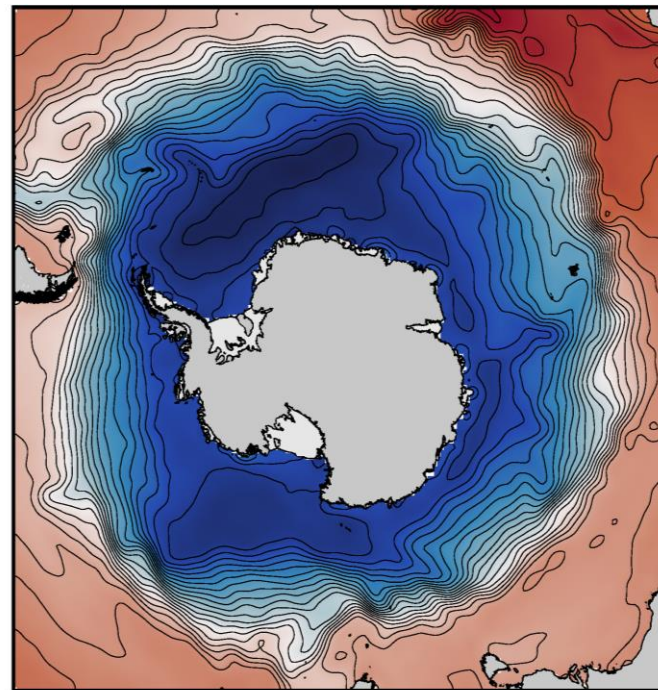
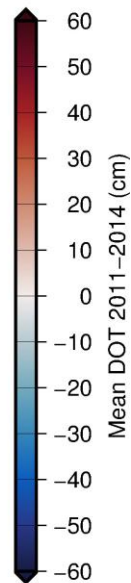
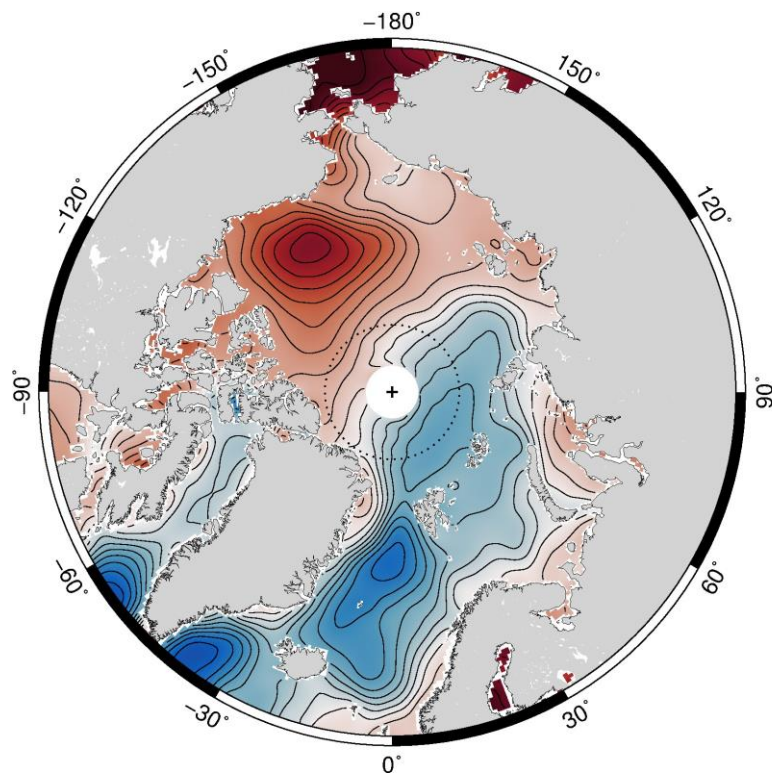
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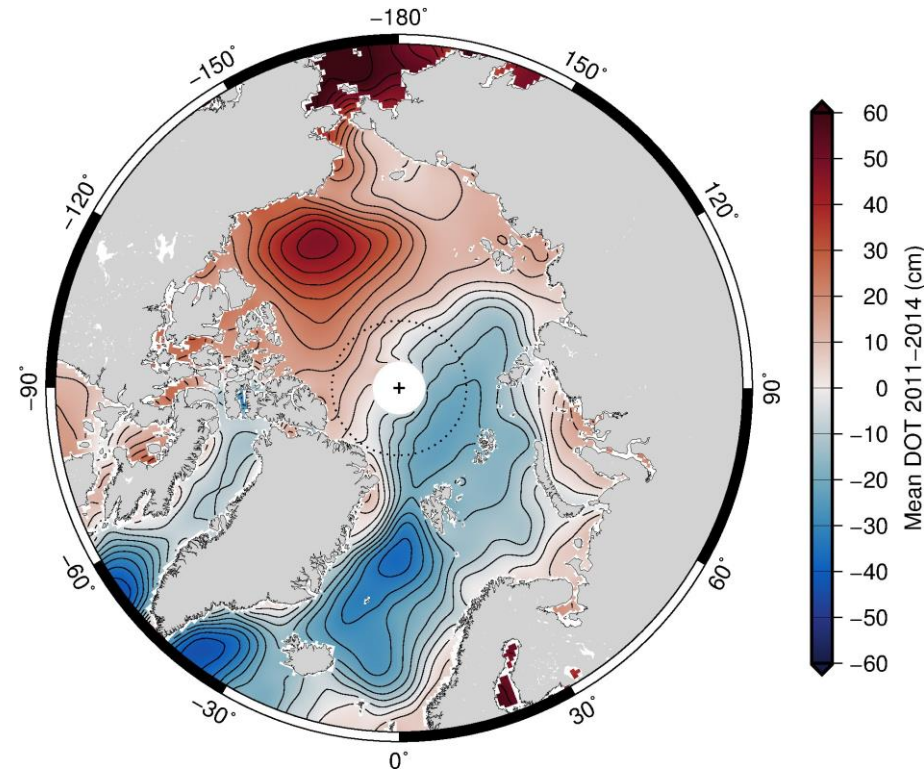
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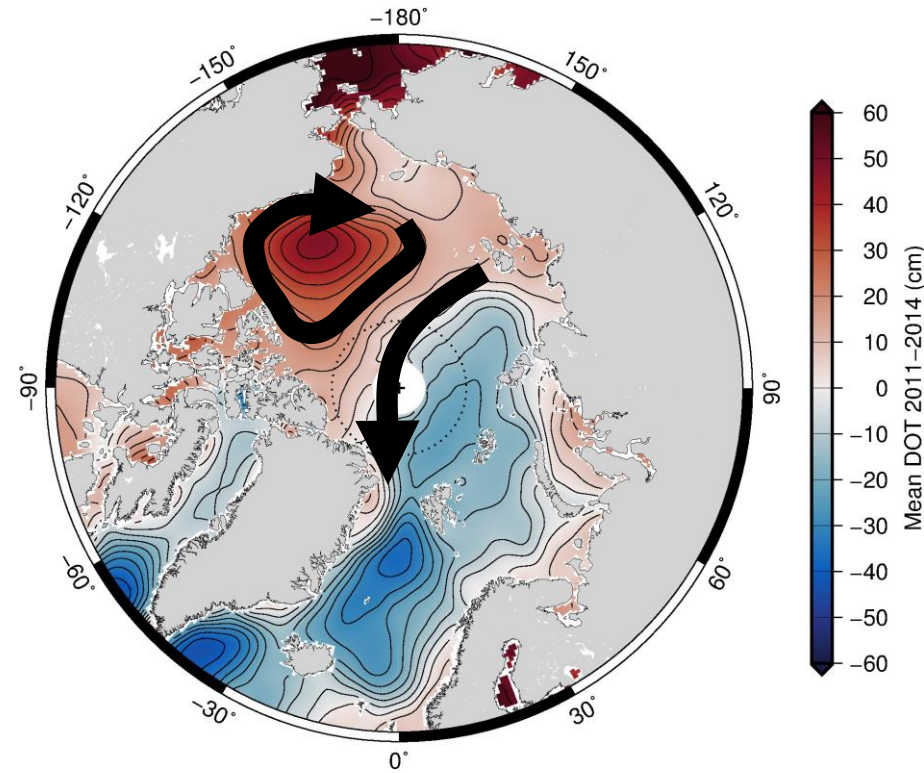
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3. The Arctic Ocean – Mean dynamic topography



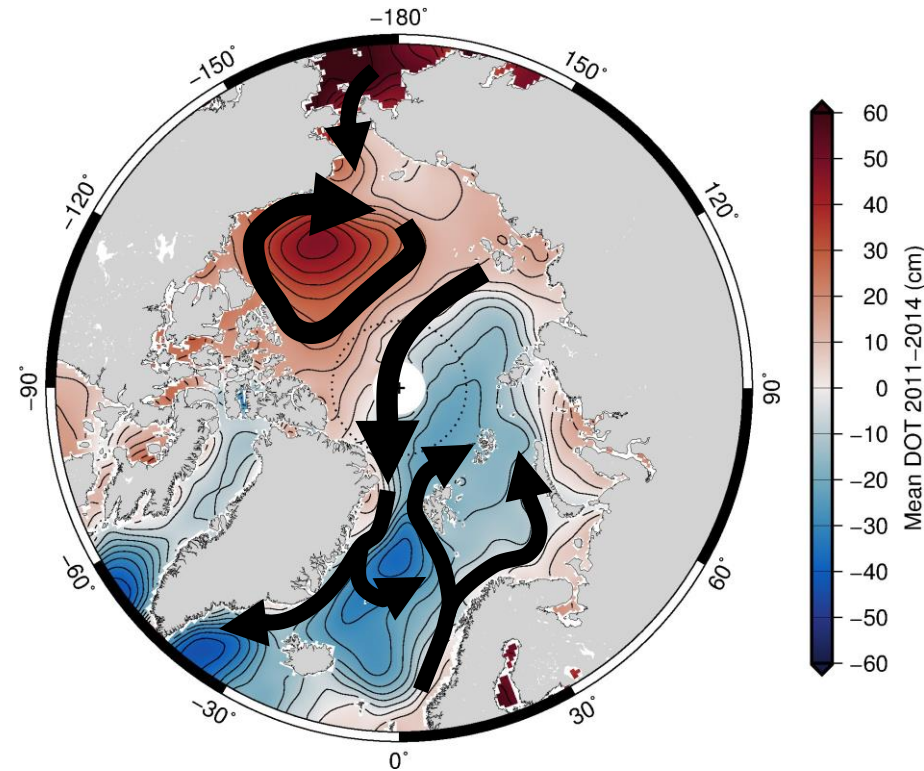
- Arctic DOT generally slopes from Pacific sector to Atlantic sector

3. The Arctic Ocean – Mean dynamic topography



- Arctic DOT generally slopes from Pacific sector to Atlantic sector
- Arctic circulation dominated by
 - Transpolar drift
 - Beaufort Gyre

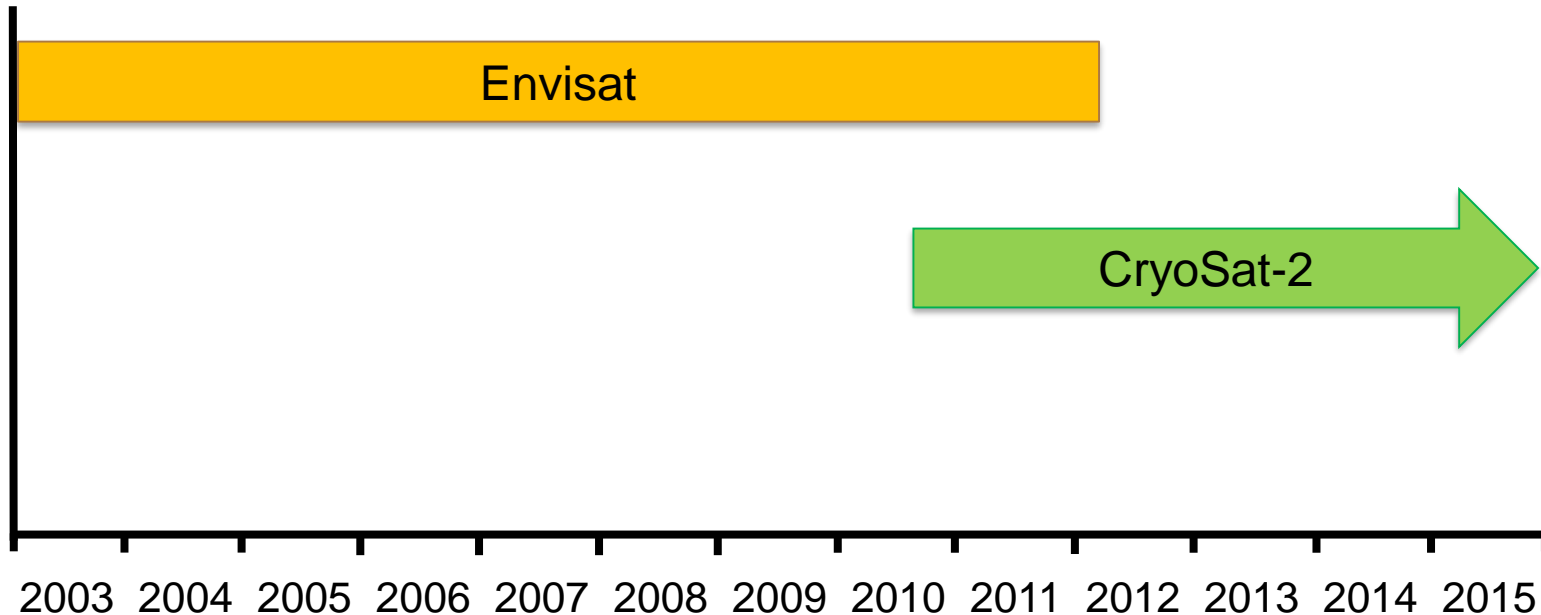
3. The Arctic Ocean – Mean dynamic topography



- Arctic DOT generally slopes from Pacific sector to Atlantic sector
- Arctic circulation dominated by
 - Transpolar drift
 - Beaufort Gyre
- Other important features
 - Atlantic/Pacific inflow
 - East Greenland current
 - Greenland Sea Gyre

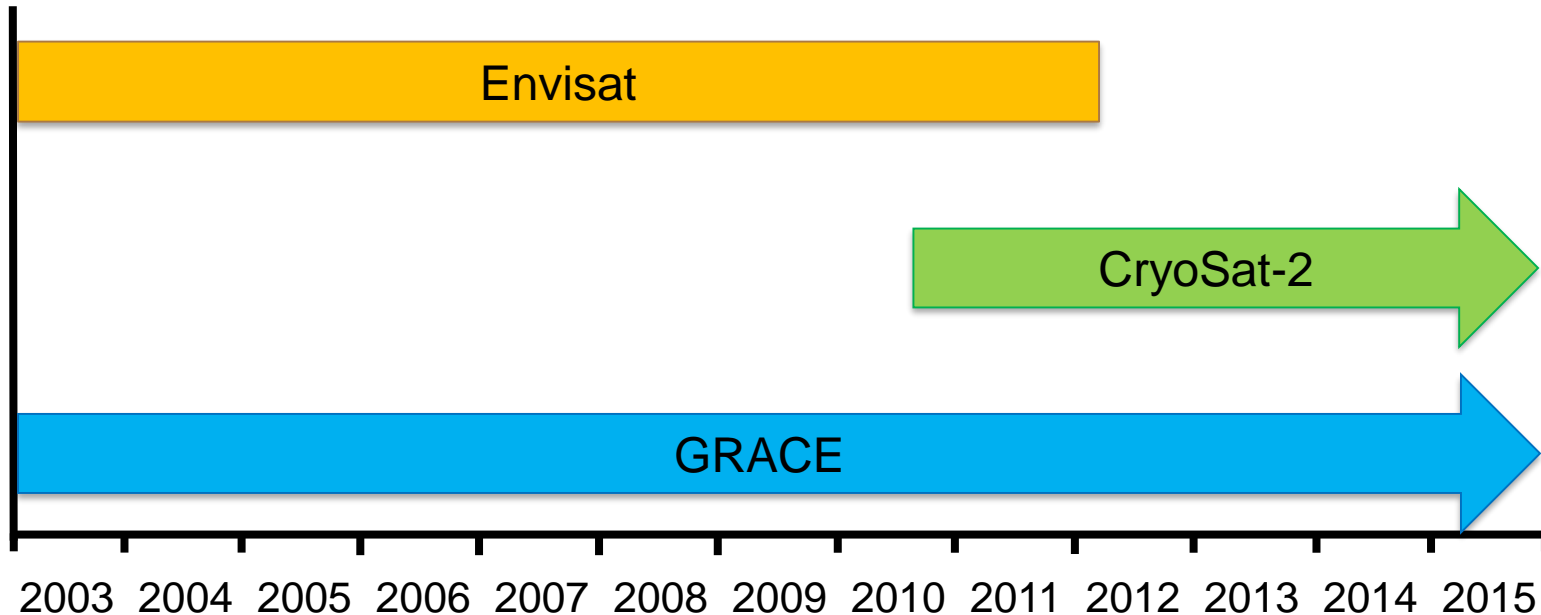
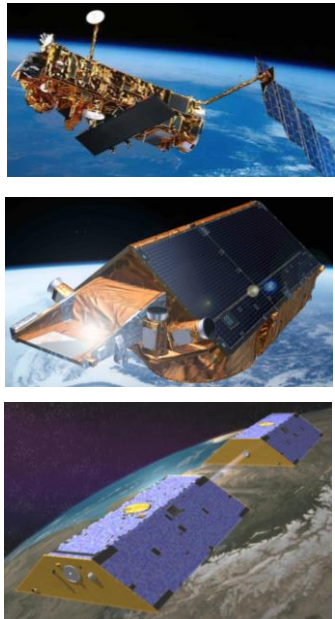
3. The Arctic Ocean – data

- Produced data record spanning 2003-2014



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- Also have GRACE ocean mass data for this period



3. The Arctic Ocean – data

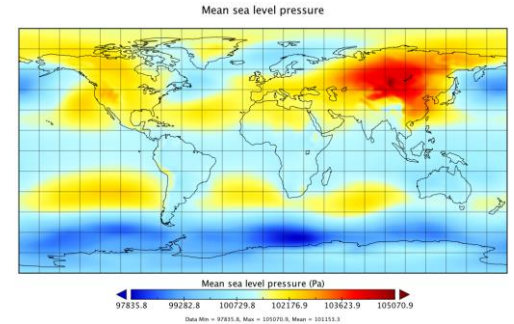
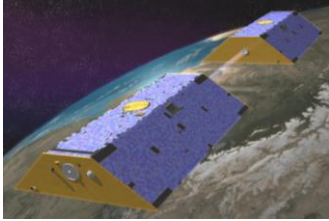
Sea level equation:

$$\underbrace{\frac{P'_b}{\rho_o g}}_{\text{Ocean bottom pressure anomaly}} = \underbrace{\eta'}_{\text{Dynamic ocean topography}} + \underbrace{\frac{1}{\rho_o} \int_{-H}^0 \rho' dz}_{\text{Steric height anomaly}} + \underbrace{\frac{\bar{P}'_a}{\rho_o g}}_{\text{Global atmospheric pressure anomaly over the ocean}}$$

3. The Arctic Ocean – data

Sea level equation:

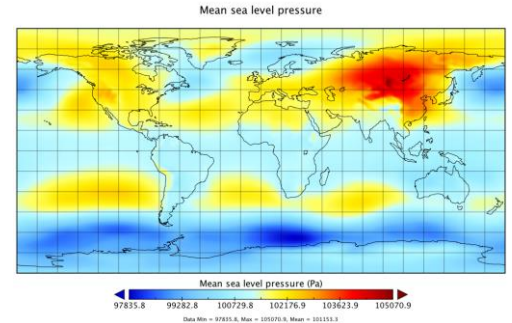
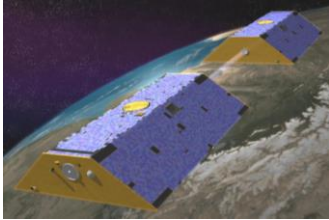
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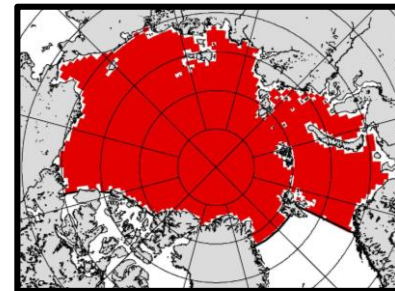
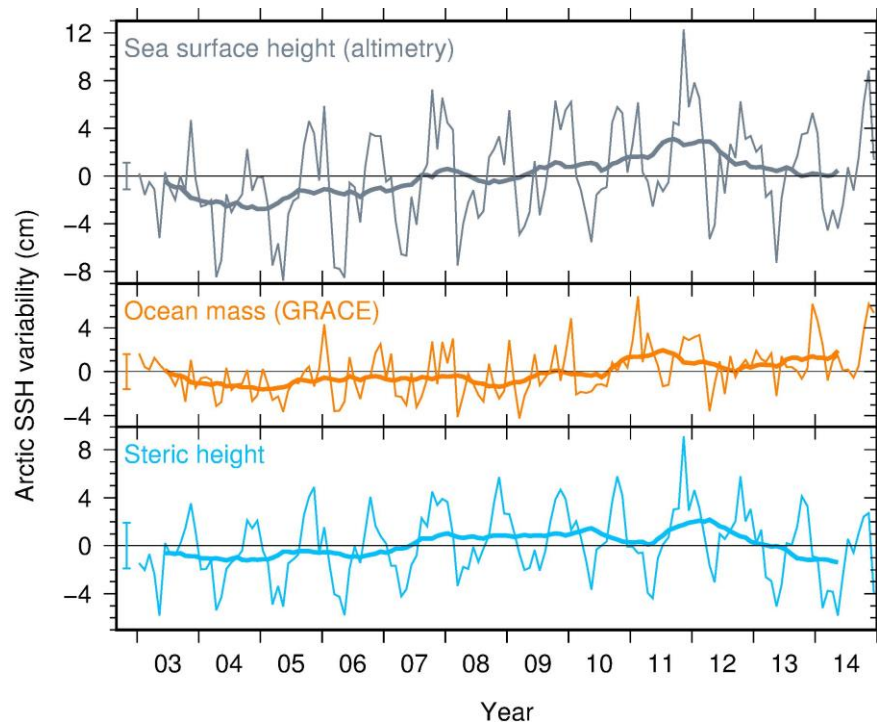
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Sea level equation:

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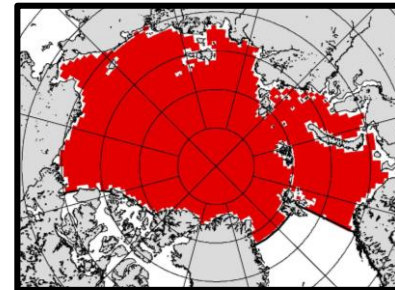
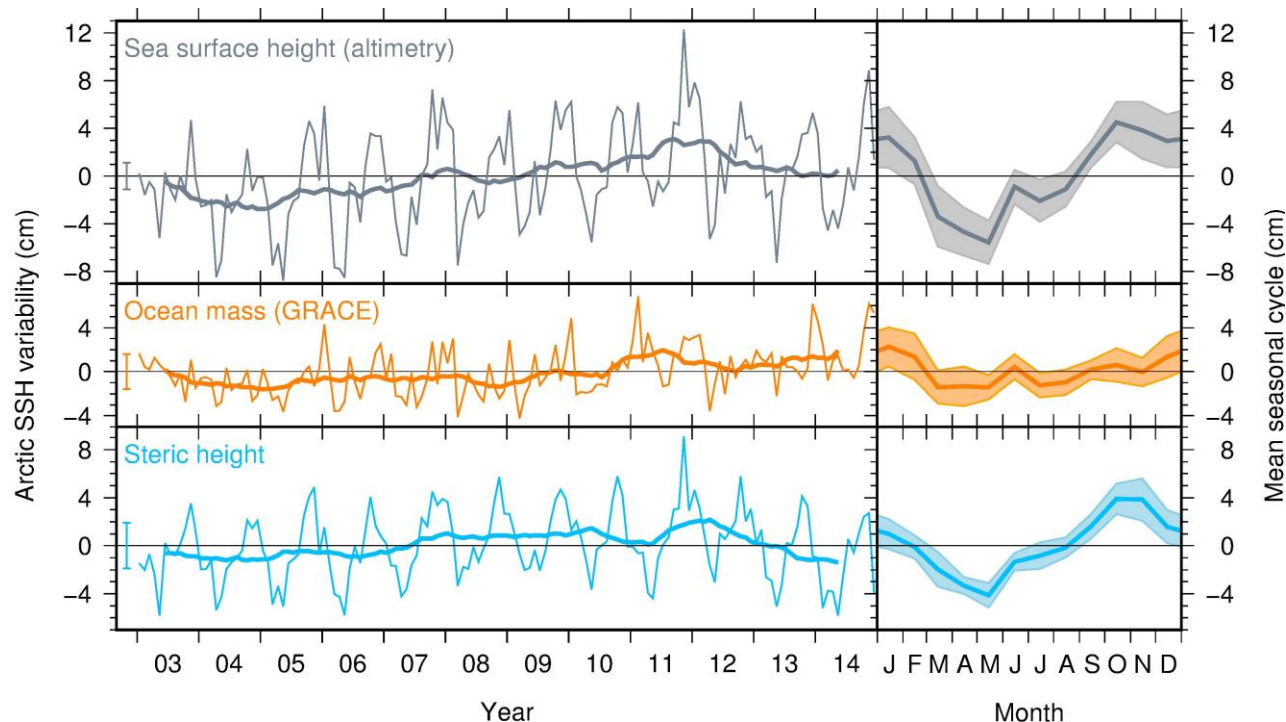


3. The Arctic Ocean – seasonal cycle



Armitage et al. (2016), "Arctic sea surface height variability and change from satellite radar altimetry and GRACE, 2003-2014", *JGR-Oceans*, 121

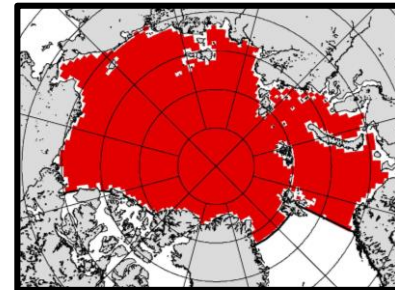
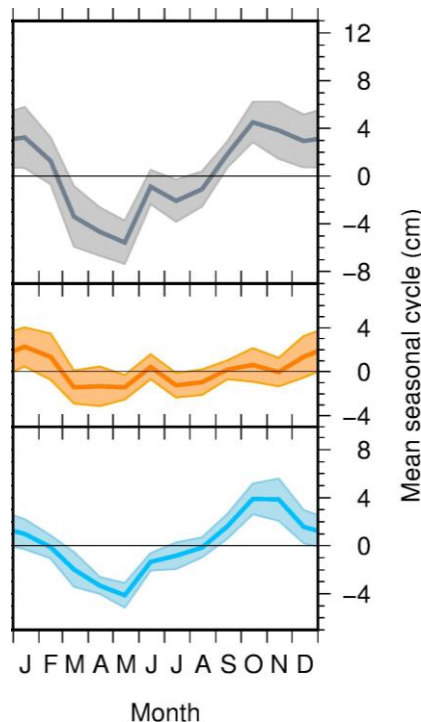
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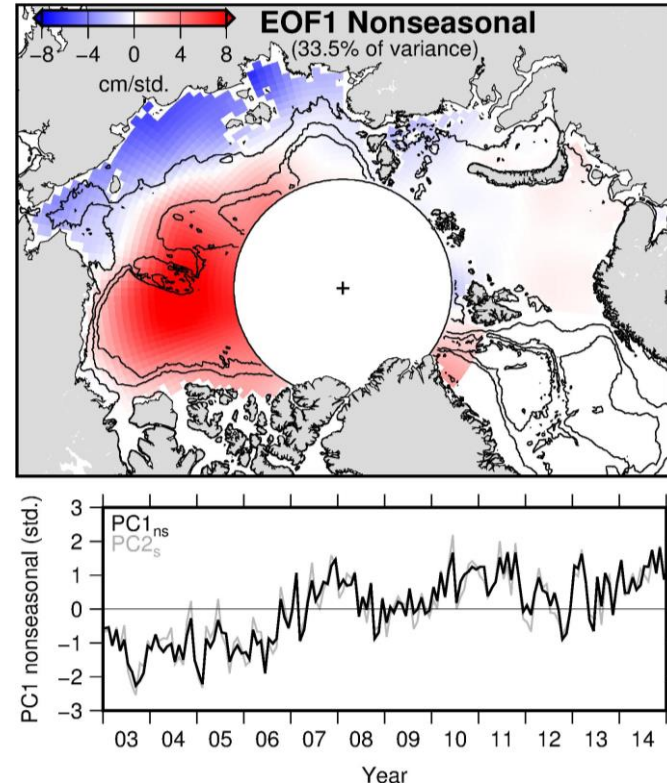
3. The Arctic Ocean – seasonal cycle

- Seasonal cycle of steric height dominates SSH variability (39% of total variability)
 - Summertime freshwater input from rivers, P-E, sea ice melt, Bering Strait inflow
 - Wintertime freshwater reduction from sea ice formation, Fram Strait export



3. The Arctic Ocean – freshwater accumulation

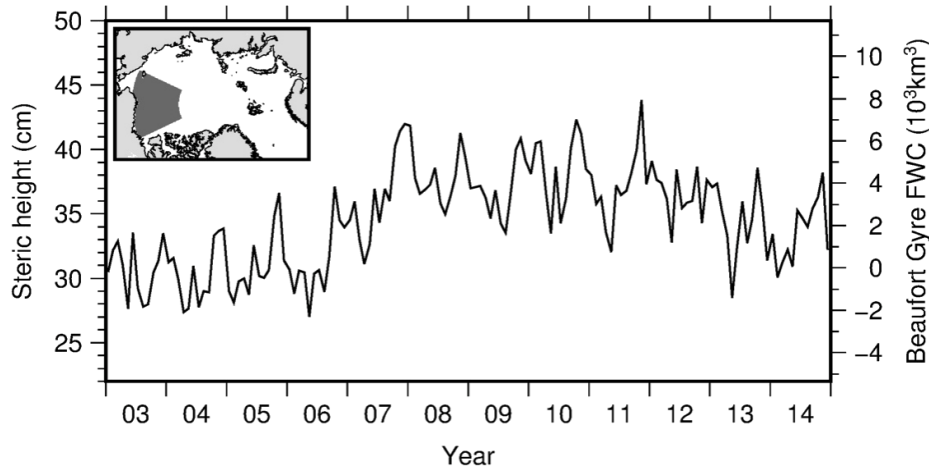
- Non-seasonal SSH variability is dominated by regional changes in freshwater storage
 - Beaufort Gyre freshwater accumulation signal accounts for 1/3 of non-seasonal variability
 - Concurrent reductions in freshwater on Siberian shelf seas



Armitage et al. (2016), "Arctic sea surface height variability and change from satellite radar altimetry and GRACE, 2003-2014", *JGR-Oceans*, 121

3. The Arctic Ocean – freshwater accumulation

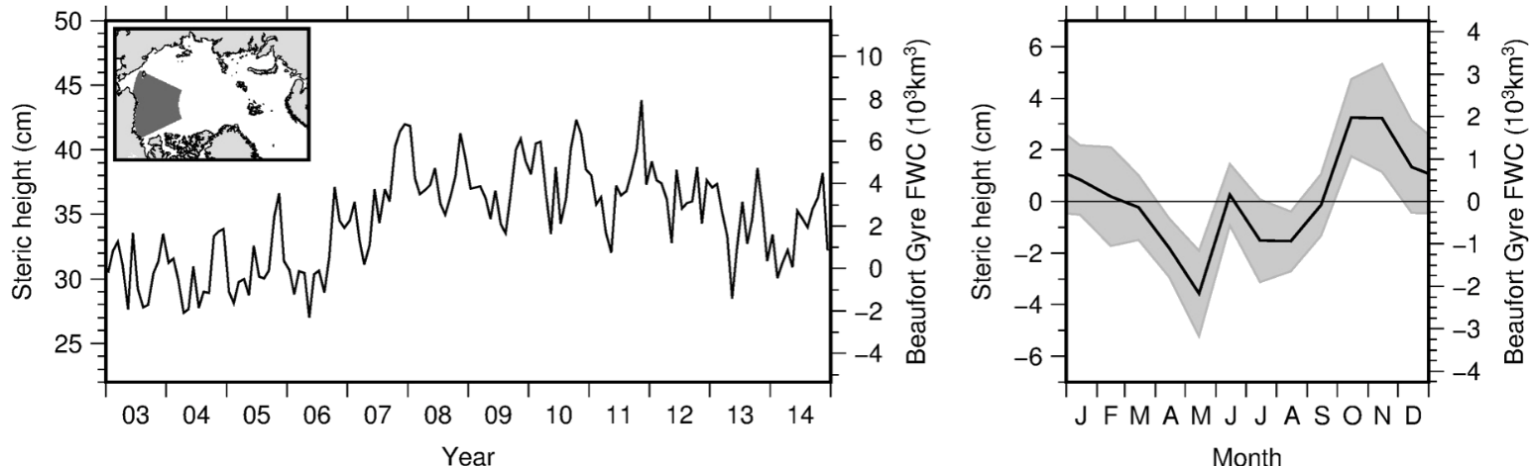
- Can use steric height to estimate FW accumulation in BG
 - +4,600 km³ in 2010 relative to 2003-06; dominated by increase in 2007-08



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3. The Arctic Ocean – freshwater accumulation

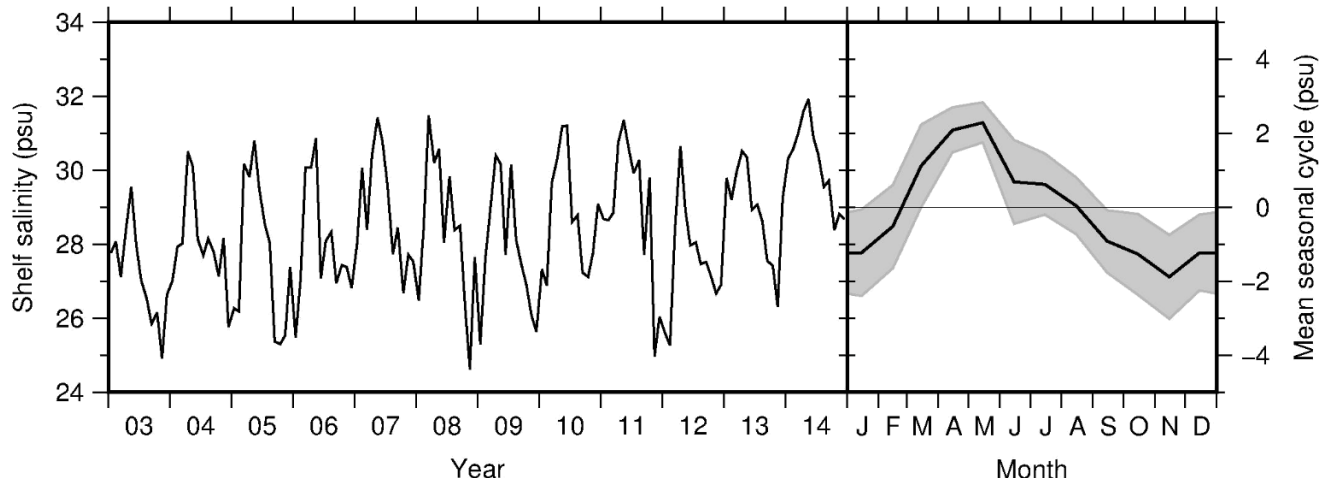
- Can use steric height to estimate FW accumulation in BG
 - +4,600 km³ in 2010 relative to 2003-06; dominated by increase in 2007-08
- Seasonal FW content cycle reflects interplay between sea ice/meteorological FW input and seasonal cycle of Ekman pumping



Armitage et al. (2016), "Arctic sea surface height variability and change from satellite radar altimetry and GRACE, 2003-2014", *JGR-Oceans*, 121

3. The Arctic Ocean – Siberian Shelf Seas salinity

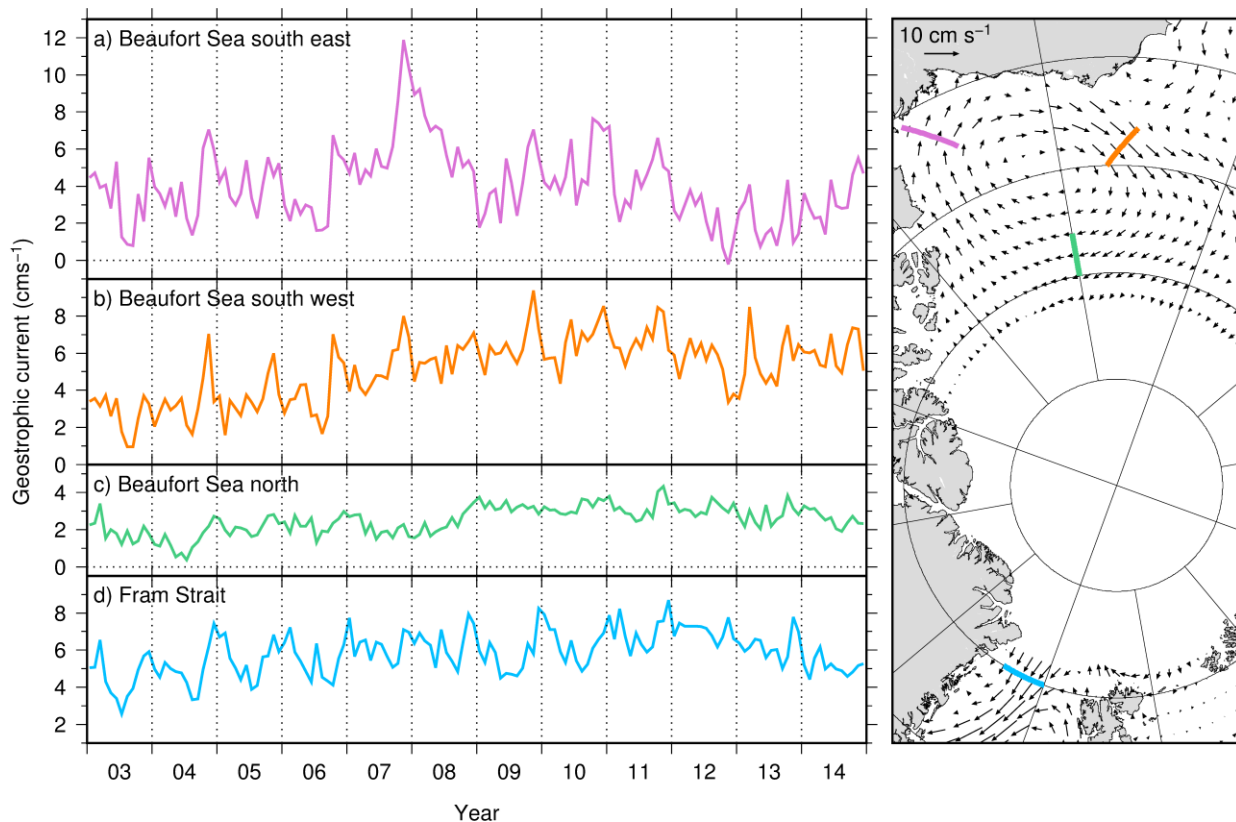
- Find an increase in shelf seas salinity of $+0.15$ psu/year
 - Corresponds to a loss of ~ 180 km³ of freshwater over time period
- Seasonal cycle mainly reflects seasonal river runoff and sea ice growth /melt



Armitage et al. (2016), "Arctic sea surface height variability and change from satellite radar altimetry and GRACE, 2003-2014", *JGR-Oceans*, 121

3. The Arctic Ocean – geostrophic circulation

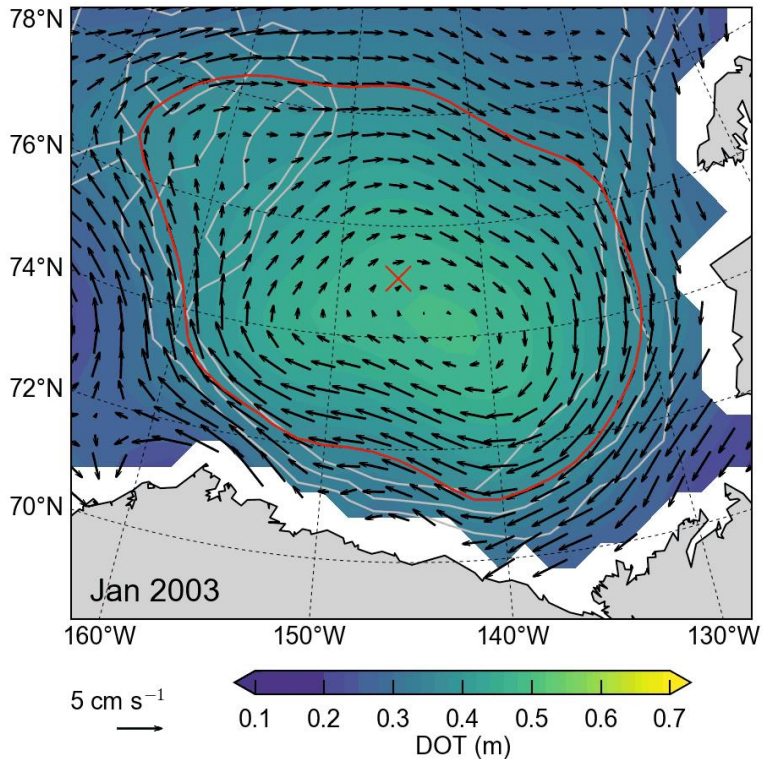
- Sea level changes associated with changing surface geostrophic circulation
- Anomalous circulation in the BG region in 2007
- Coincides with significant FW accumulation



Armitage et al. (2017), "Arctic Ocean surface geostrophic circulation 2003-2014", *The Cryosphere*, 11.

3. The Arctic Ocean – geostrophic circulation

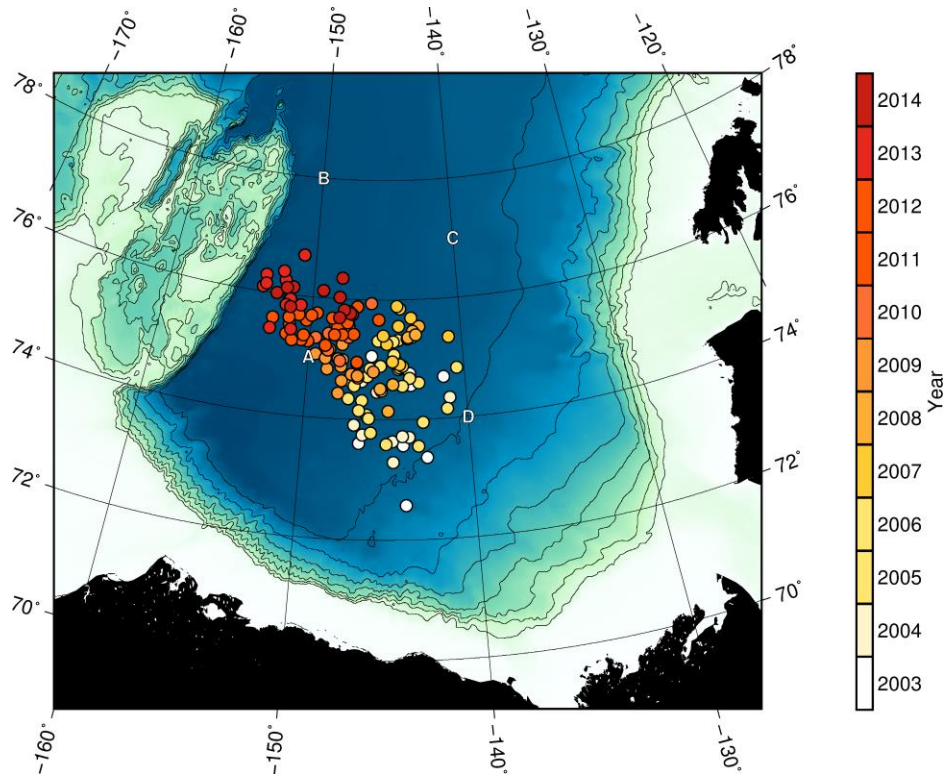
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Armitage et al. (2017), "Arctic Ocean surface geostrophic circulation 2003-2014", *The Cryosphere*, 11.

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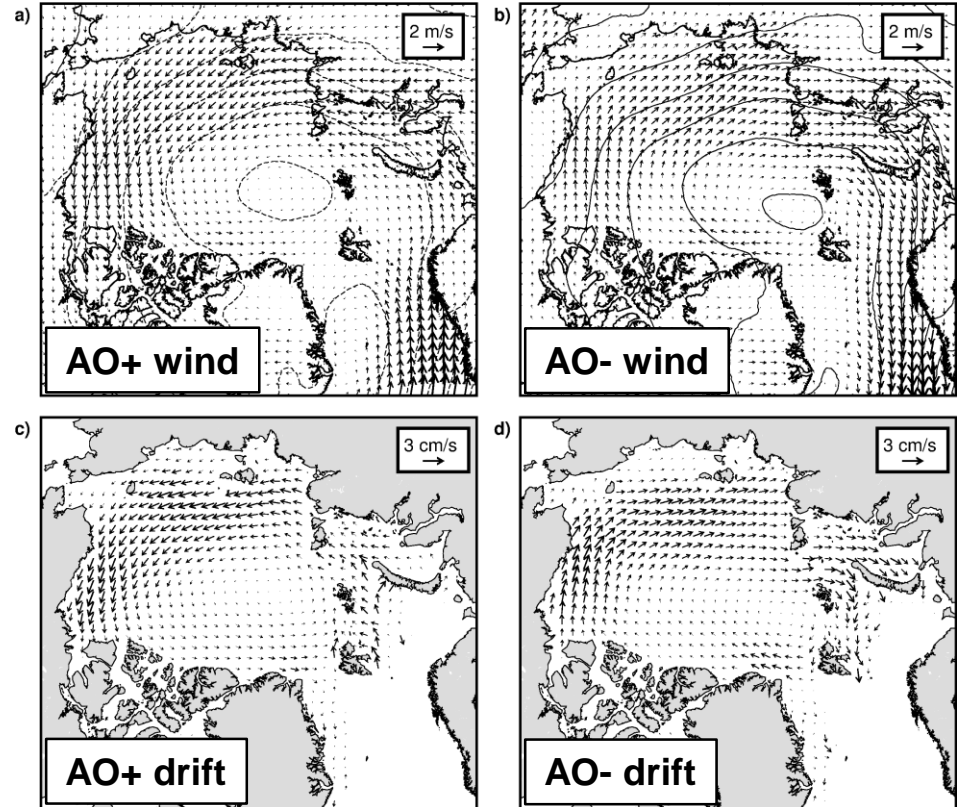
- Beaufort Gyre also shifted position by ~300km
- Gyre center close to Chukchi plateau by end of time period
- Implications for gyre interactions/dissipation with bathymetry



Armitage et al. (2017), "Arctic Ocean surface geostrophic circulation 2003-2014", *The Cryosphere*, 11.

3. The Arctic Ocean – climate variability

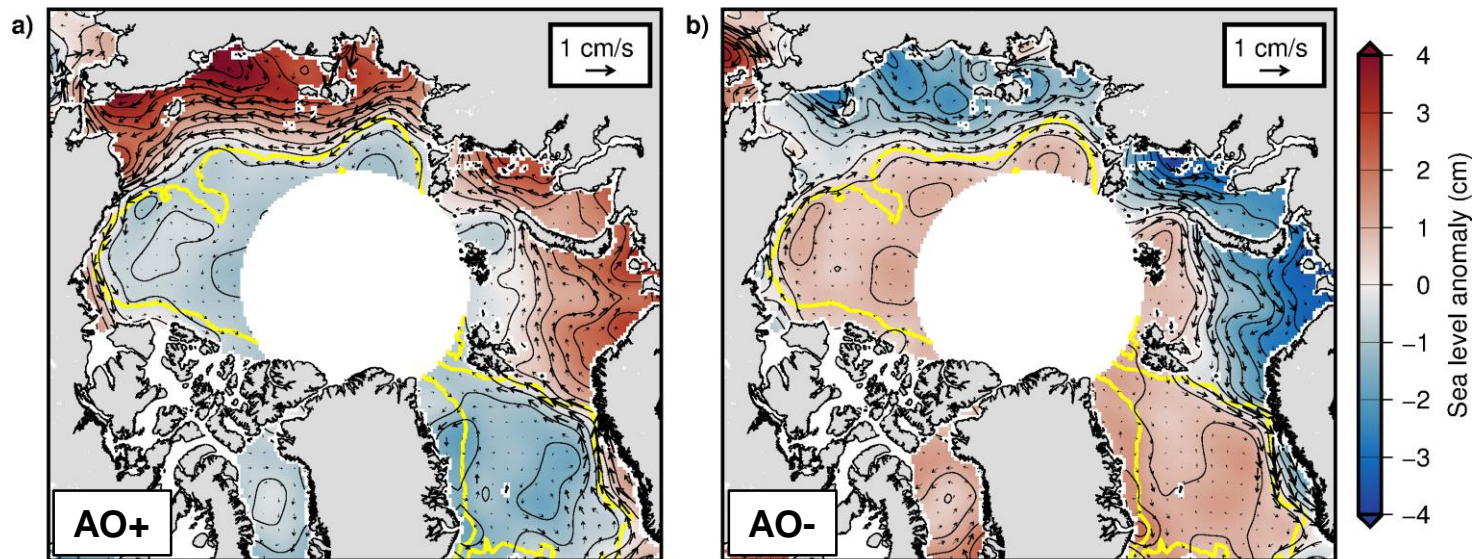
- Arctic Oscillation (AO) is leading mode of extratropical northern hemisphere atmospheric variability
- Pressure anomalies drive (anti)cyclonic wind anomalies
 - Drives ice drift anomalies in response



Armitage et al. (2018), "Arctic sea level and surface circulation response to the Arctic Oscillation", *GRL*, in review.

3. The Arctic Ocean – climate variability

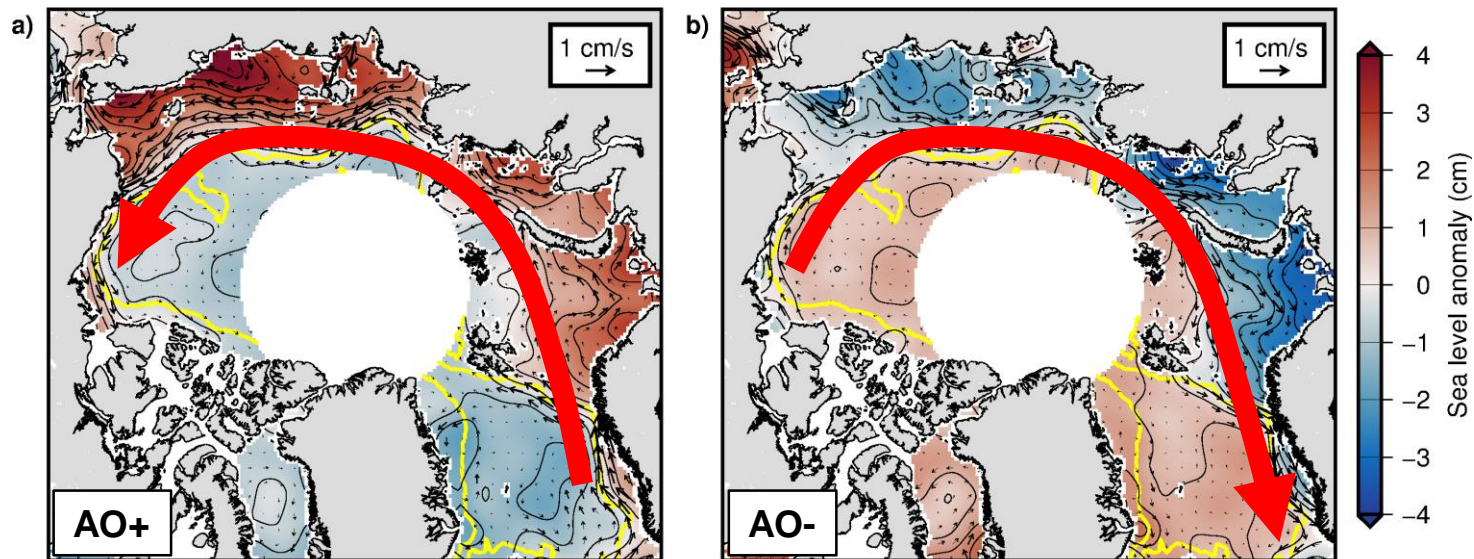
- Opposing sea level response between shelves/deep basin
- Sets up along-shelf geostrophic current anomalies



Armitage et al. (2018), "Arctic sea level and surface circulation response to the Arctic Oscillation", *GRL*, in review.

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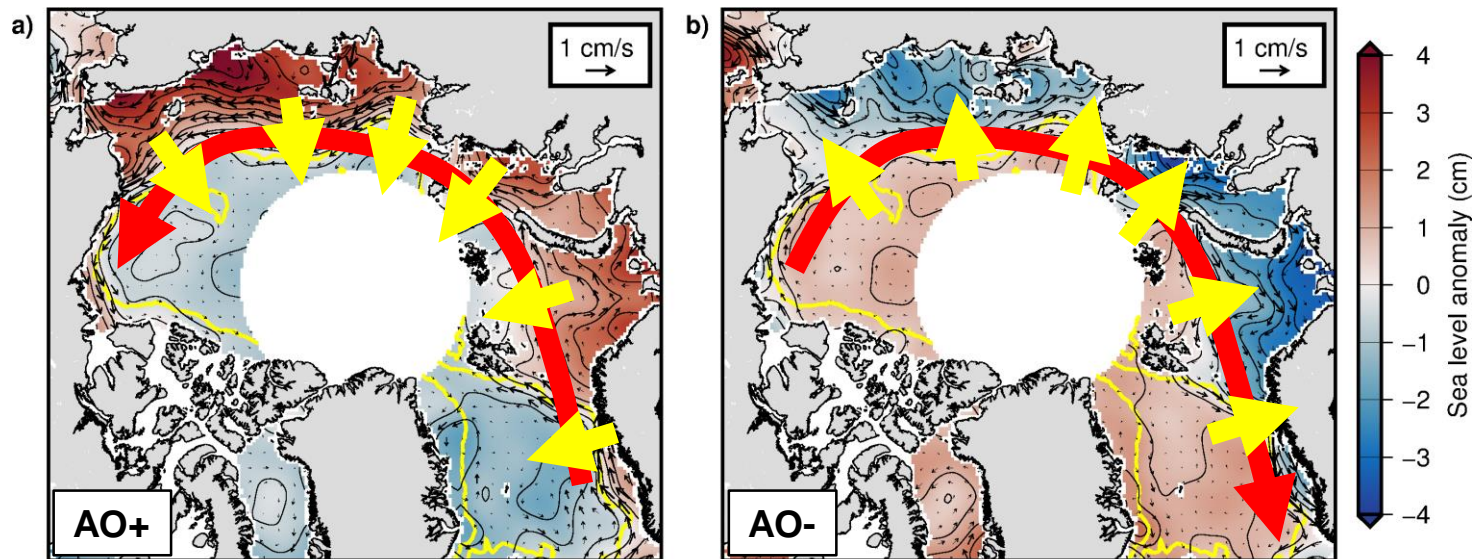
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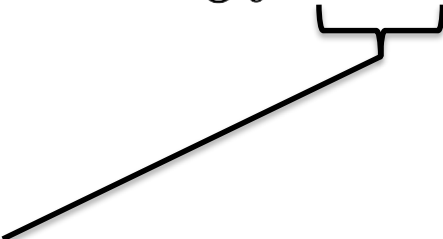
3. Beaufort Gyre energetics & freshwater equilibration

Oceanic mechanical energy budget:

$$\frac{\partial}{\partial t} (KE + APE) = W - D$$

3. Beaufort Gyre energetics & freshwater equilibration

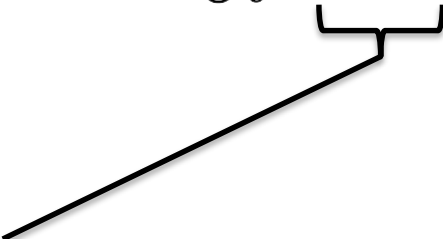
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Kinetic energy
i.e., $\frac{1}{2} mv^2$

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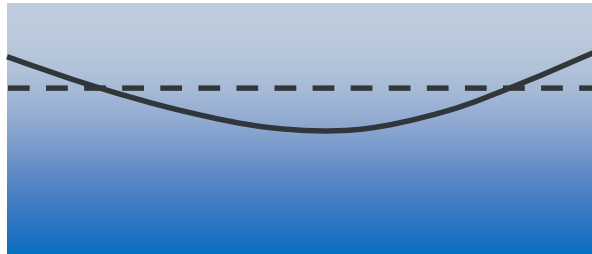
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Available potential
energy



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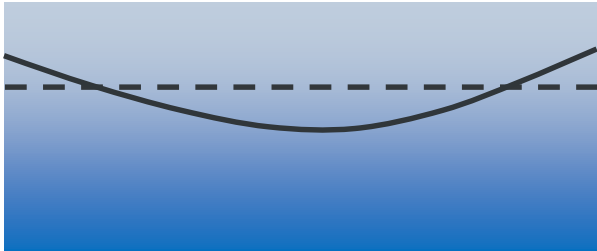
Oceanic mechanical energy budget:

$$\frac{\partial}{\partial t} (\underbrace{\cancel{KE}}_{\text{Kinetic energy}} + \underbrace{APE}_{\text{Available potential energy}}) = \underbrace{W - D}_{\text{Work done on the geostrophic circulation}}$$

Kinetic energy
i.e., $\frac{1}{2}mv^2$

Available potential energy

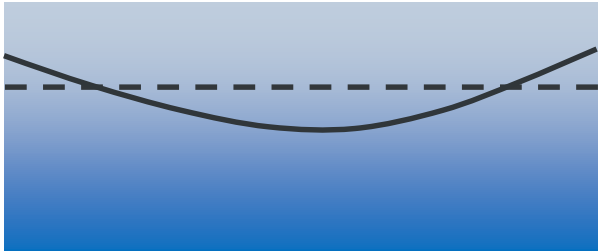
Work done on the geostrophic circulation
 $W = \tau_o \cdot \mathbf{u}_g$



The diagram illustrates the oceanic mechanical energy budget equation. The equation is $\frac{\partial}{\partial t} (\cancel{KE} + APE) = W - D$. The term \cancel{KE} is crossed out with a red 'X'. Brackets are placed under \cancel{KE} , APE , and $W - D$. Lines connect these brackets to their respective labels: 'Kinetic energy i.e., $\frac{1}{2}mv^2$ ' for \cancel{KE} , 'Available potential energy' for APE , and 'Work done on the geostrophic circulation $W = \tau_o \cdot \mathbf{u}_g$ ' for $W - D$. Below the equation is a cross-section of the ocean with a blue gradient. A dashed horizontal line represents the mean sea level, and a solid black line shows a depression in the sea surface, representing a gyre.

3. Beaufort Gyre energetics & freshwater equilibration

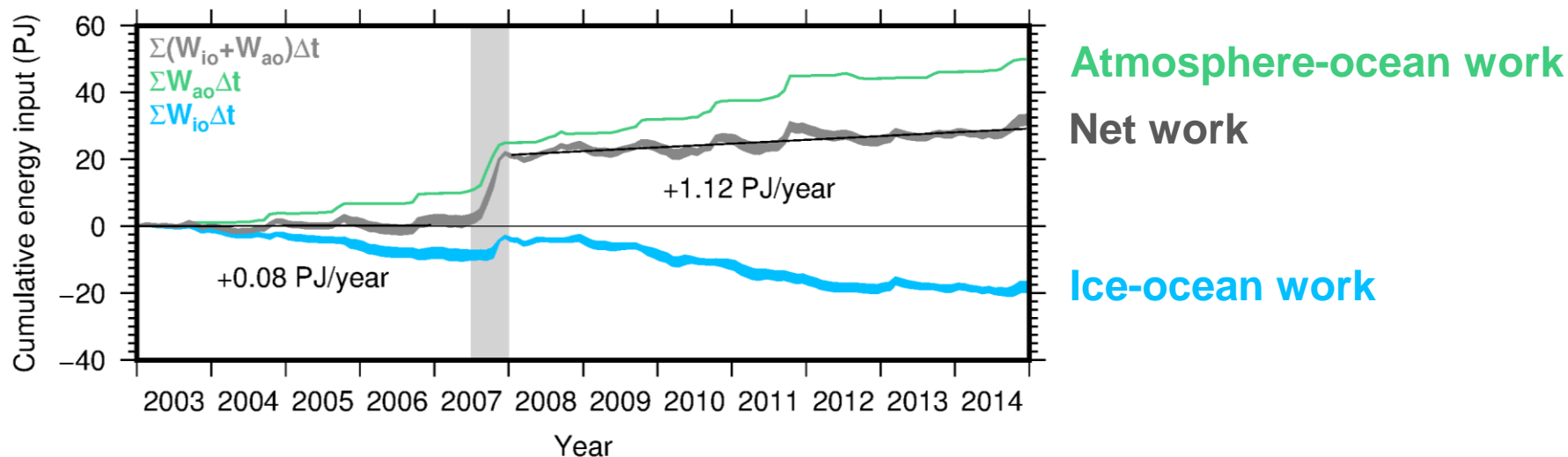
Oceanic mechanical energy budget:

$$\frac{\partial}{\partial t} (\underbrace{\cancel{KE}}_{\text{Kinetic energy i.e., } \frac{1}{2}mv^2} + \underbrace{APE}_{\text{Available potential energy}}) = \underbrace{W}_{\substack{\text{Work done on the} \\ \text{geostrophic circulation} \\ W = \tau_o \cdot \mathbf{u}_g}} - \underbrace{D}_{\text{Residual dissipation}}$$


The diagram illustrates the oceanic mechanical energy budget. At the top, the equation $\frac{\partial}{\partial t} (\cancel{KE} + APE) = W - D$ is shown. The term \cancel{KE} is crossed out with a red 'X'. Brackets connect the terms to their definitions: \cancel{KE} to 'Kinetic energy i.e., $\frac{1}{2}mv^2$ ', APE to 'Available potential energy', W to 'Work done on the geostrophic circulation $W = \tau_o \cdot \mathbf{u}_g$ ', and D to 'Residual dissipation'. Below the equation is a cross-section of the ocean. A dashed horizontal line represents the mean sea level. A solid line shows the sea surface elevation, which is depressed in the center of the Beaufort Gyre, forming a bowl shape. The water is colored with a blue gradient, darker at the bottom.

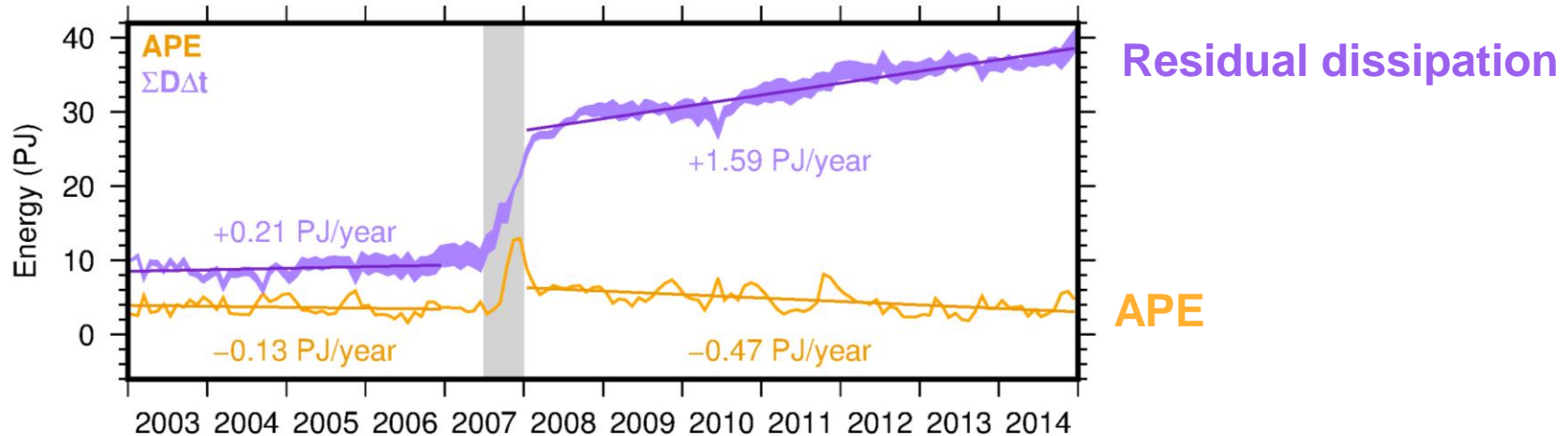
3. Beaufort Gyre energetics & freshwater equilibration

$$W = \tau_o \cdot \mathbf{u}_g [= (1 - A)\tau_{ao} \cdot \mathbf{u}_g + A\tau_{io} \cdot \mathbf{u}_g]$$



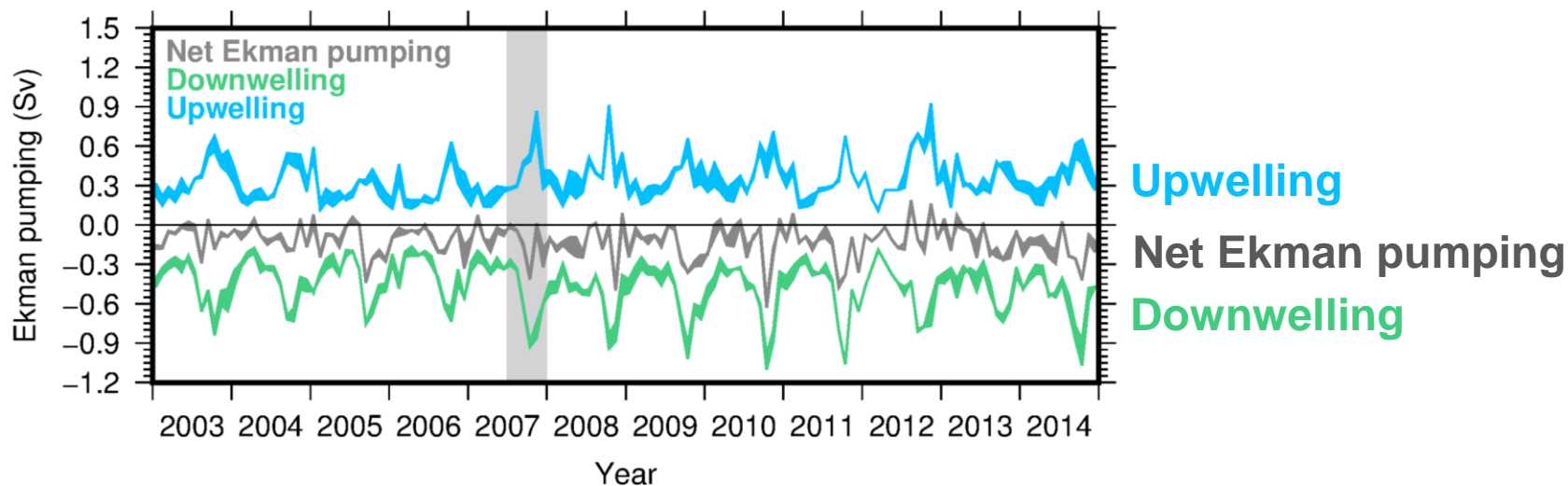
Sea ice loss and increased circulation after 2007 = net energy input

3. Beaufort Gyre energetics & freshwater equilibration



3. Beaufort Gyre energetics & freshwater equilibration

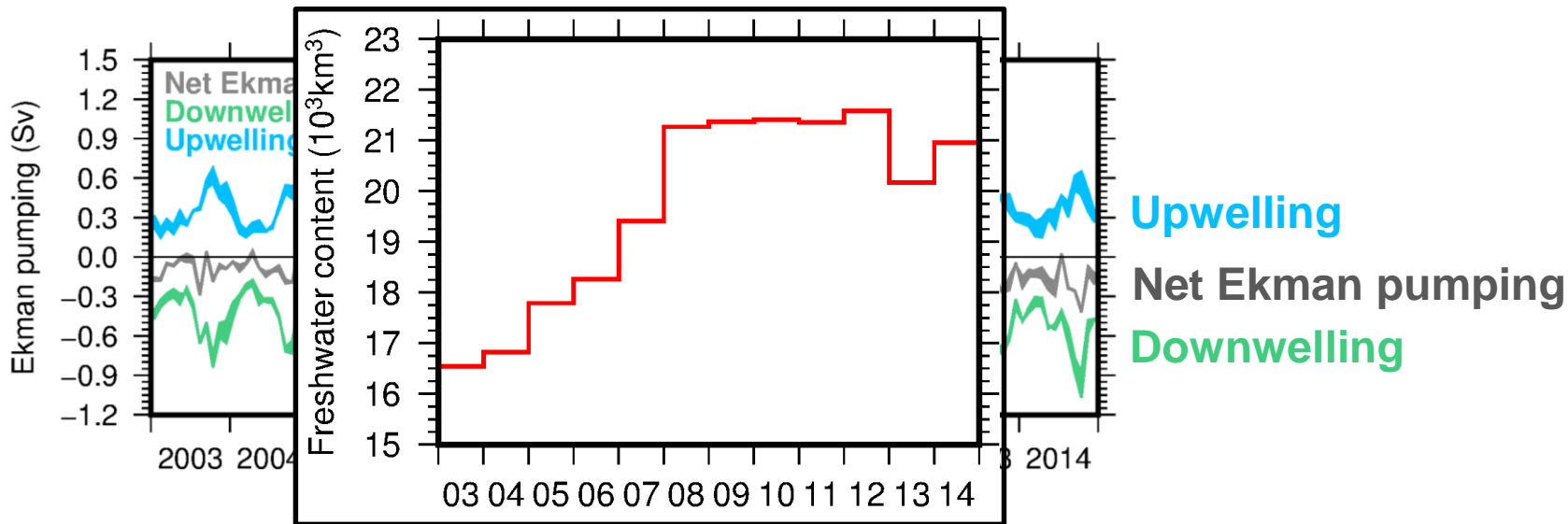
Can also calculate Ekman pumping: $w_E = \nabla \times \tau_o$



Net downwelling increased by ~30% after 2007

3. Beaufort Gyre energetics & freshwater equilibration

Can also calculate Ekman pumping: $w_E = \nabla \times \tau_o$

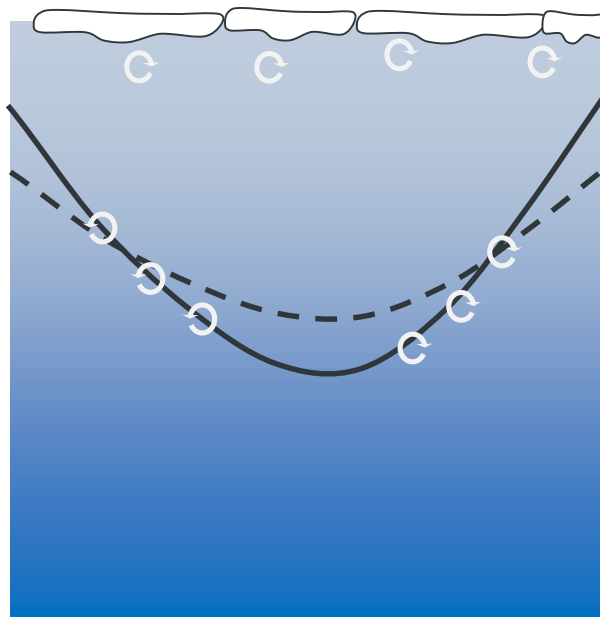


Net downwelling increased by ~30% after 2007

- but freshwater content stabilized

3. Beaufort Gyre energetics & freshwater equilibration

- Both energetics and freshwater considerations point to increased stabilizing role of **eddies**:
 - Halocline eddies act to counteract halocline steepening and dissipate freshwater
 - Transient surface eddies dissipate energy at the ice-ocean interface
- As sea ice declines further, expect to see this trend continue

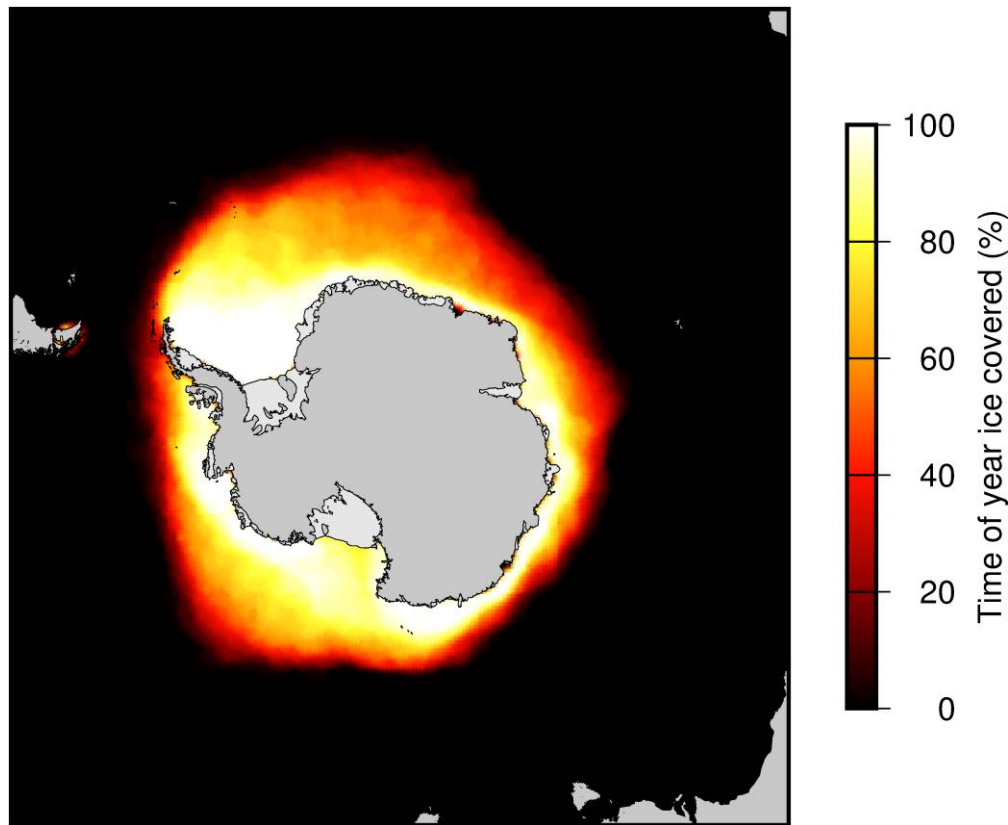


Talk outline

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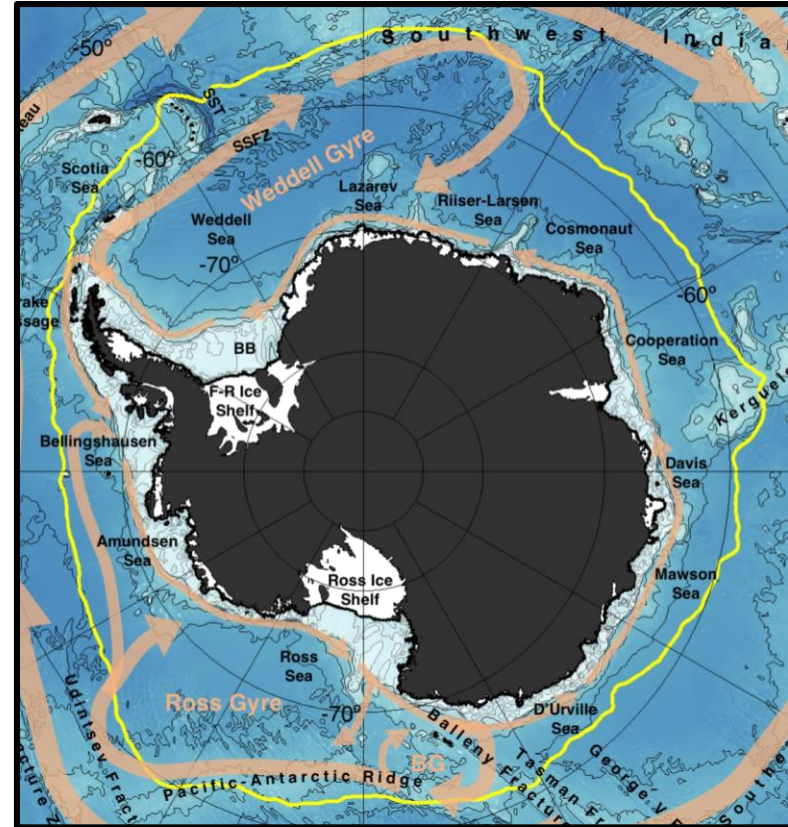
4. The Southern Ocean

- Large regions of the Southern Ocean are covered by seasonal or perennial sea ice
- Includes climatically important regions of water mass modification, surface fluxes, sea ice formation, glacial input
 - Ross/Weddell Gyres, continental shelves

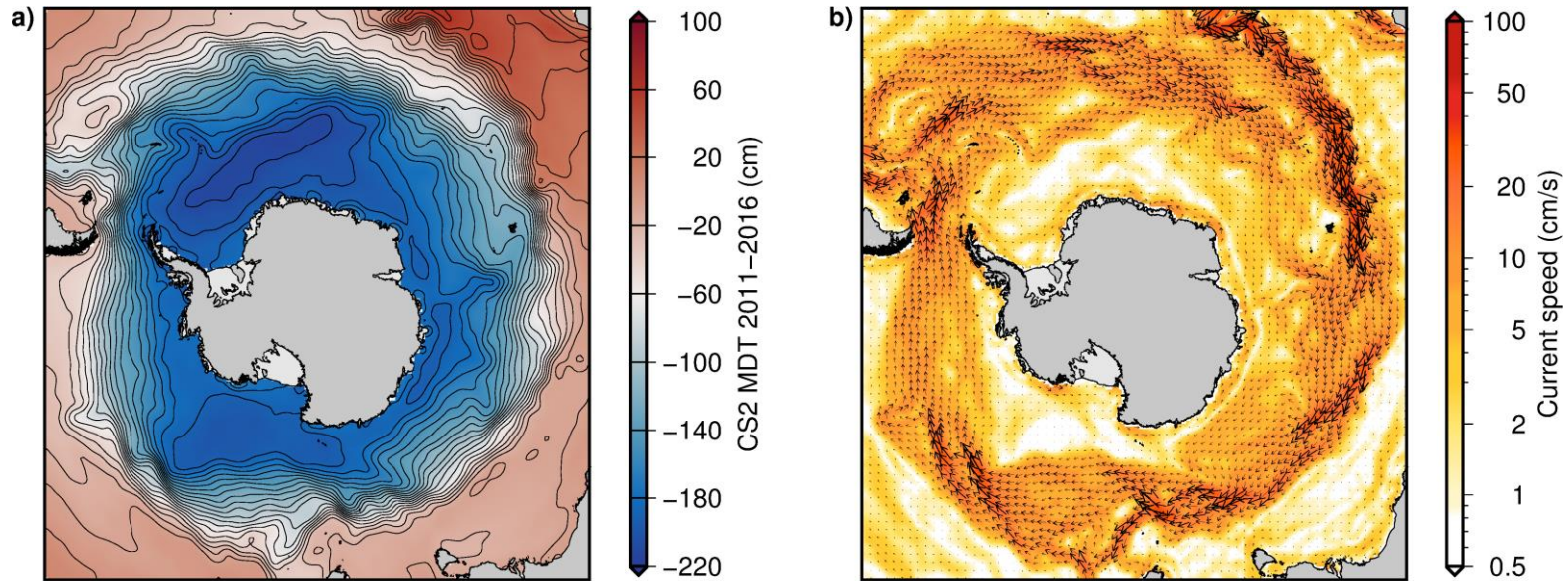


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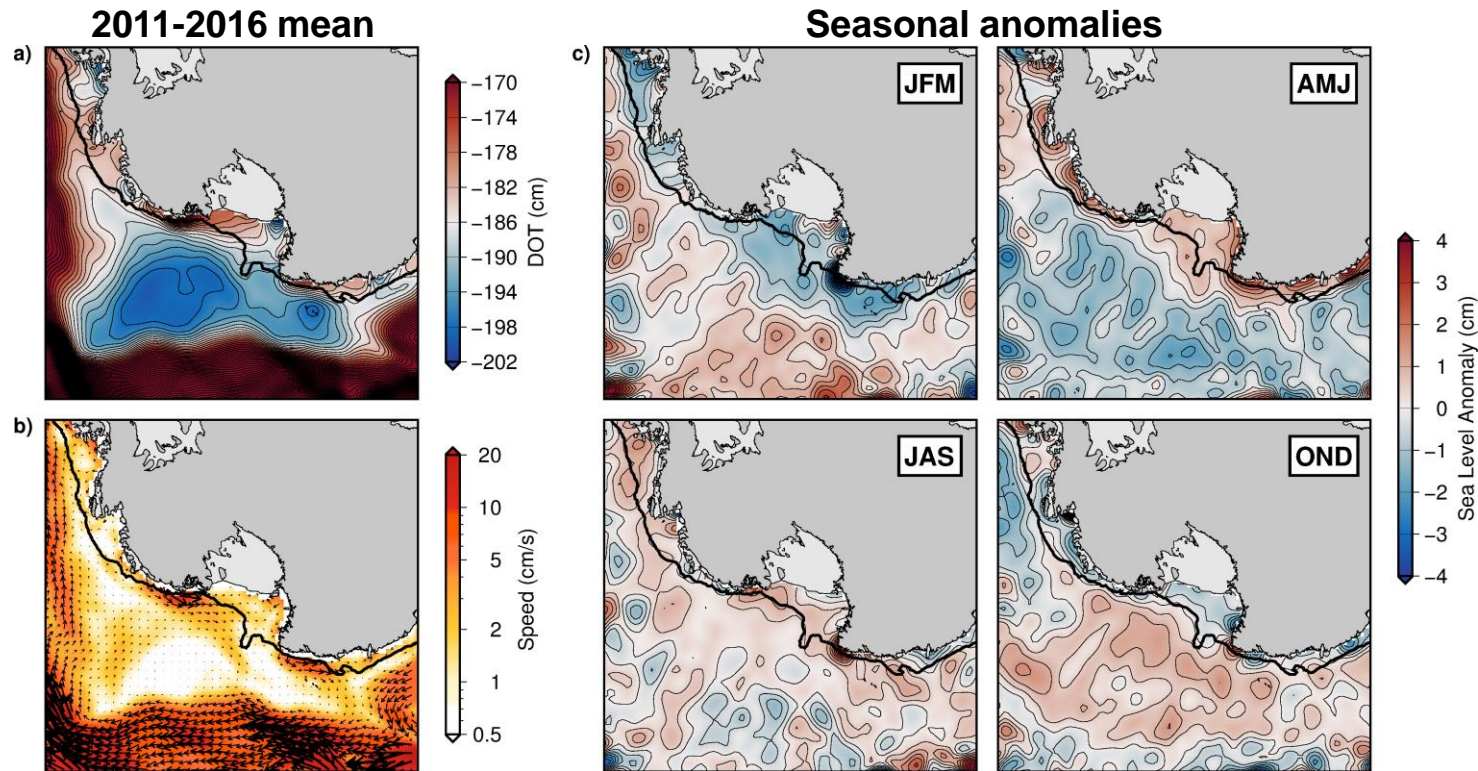
4. The Southern Ocean – Mean dynamic topography



- Low mean current speeds in Ross/Weddell gyres (0.5 cm/s)
- Antarctic slope current is an almost circumpolar feature

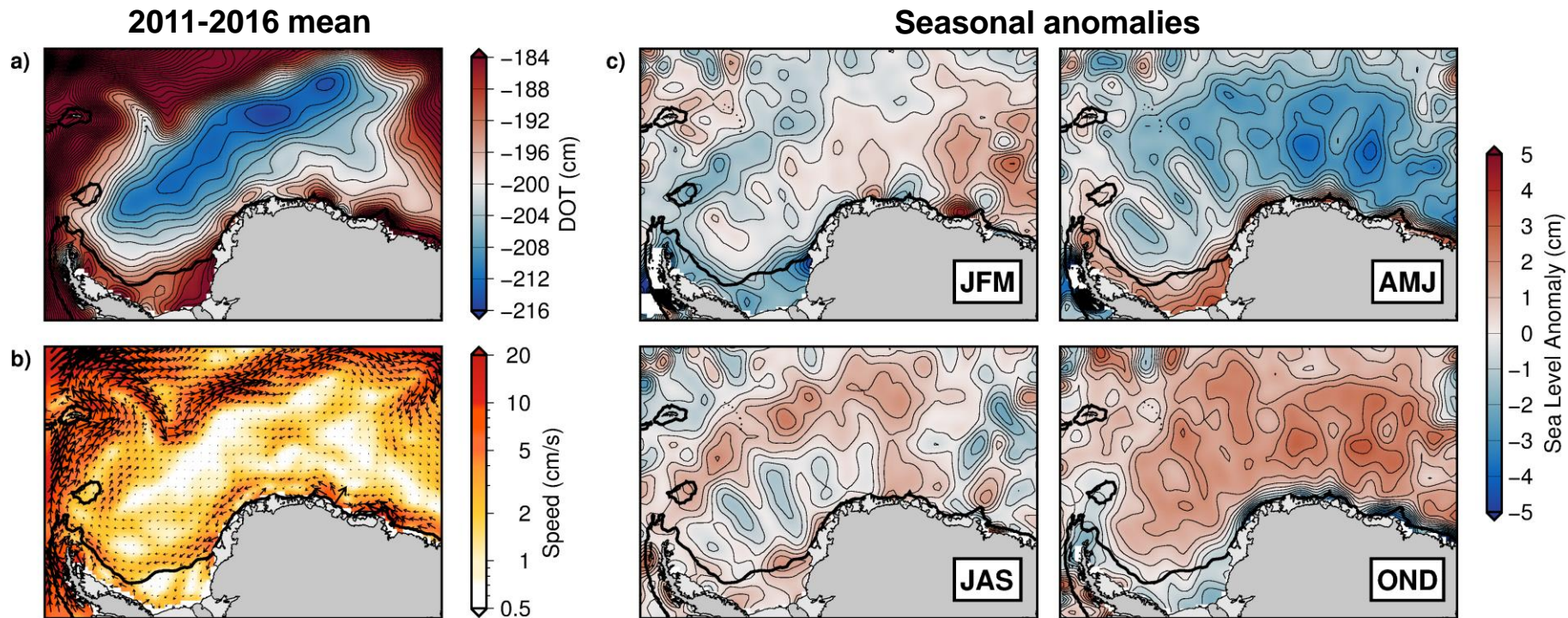
Armitage et al. (2018), "Dynamic topography and sea level anomalies of the Southern Ocean: Variability and teleconnections", *JGR-Oceans*, 123.

4. The Southern Ocean - Ross Gyre



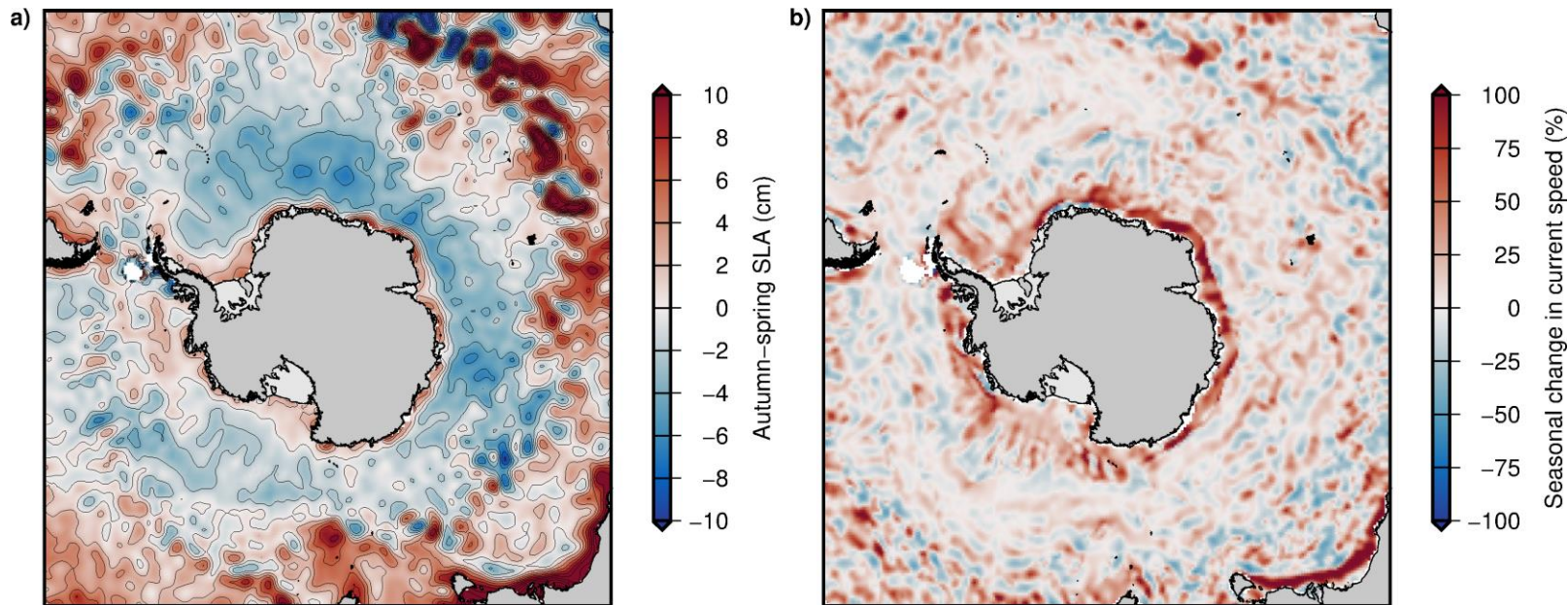
Armitage et al. (2018), "Dynamic topography and sea level anomalies of the Southern Ocean: Variability and teleconnections", *JGR-Oceans*, 123.

4. The Southern Ocean - Weddell Gyre



Armitage et al. (2018), "Dynamic topography and sea level anomalies of the Southern Ocean: Variability and teleconnections", *JGR-Oceans*, 123.

4. The Southern Ocean - seasonal cycle

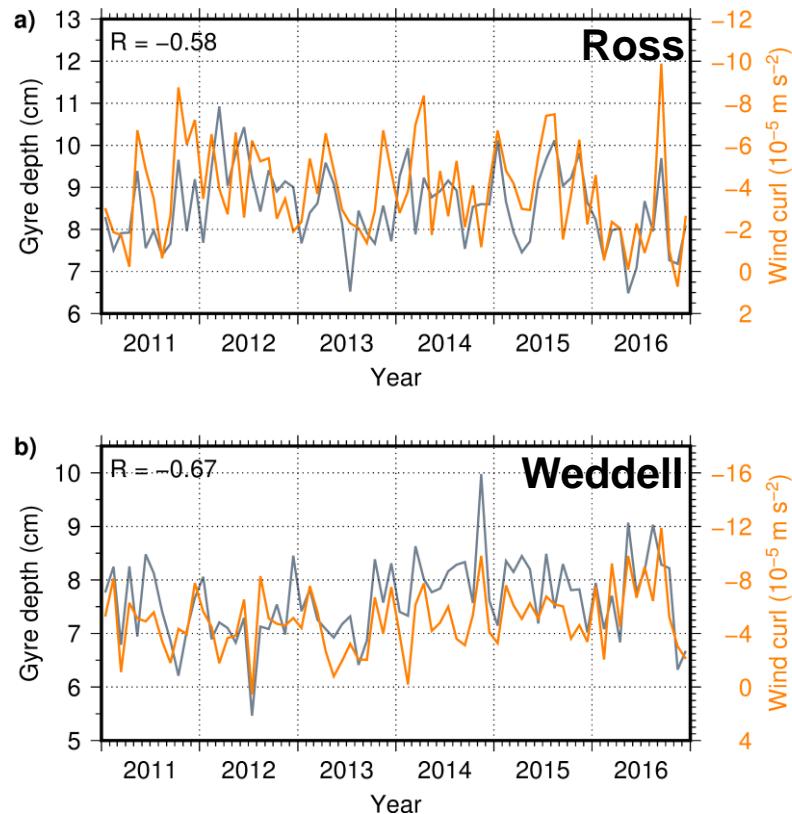


- Opposing seasonal anomalies between shelf and deeper basins
- ASC up to twice as fast in Autumn, weakest in winter and spring

Armitage et al. (2018), "Dynamic topography and sea level anomalies of the Southern Ocean: Variability and teleconnections", *JGR-Oceans*, 123.

4. The Southern Ocean - Ross/Weddell Gyre variability

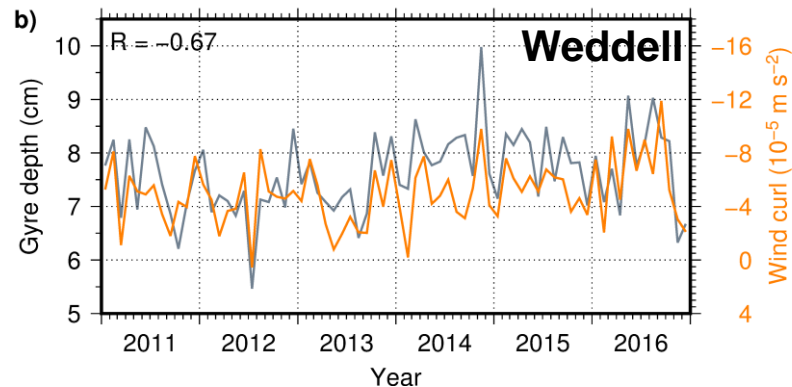
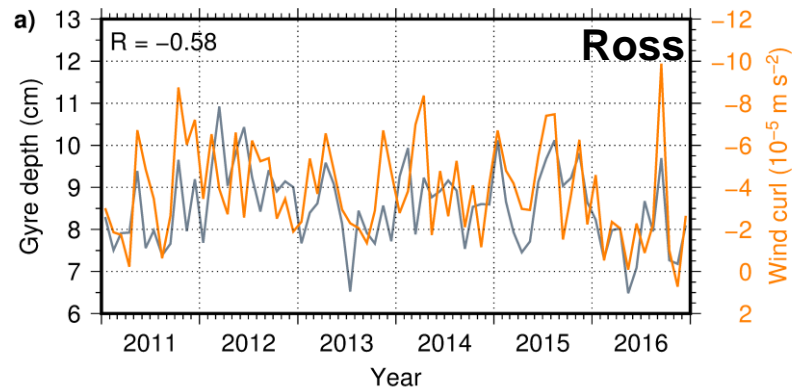
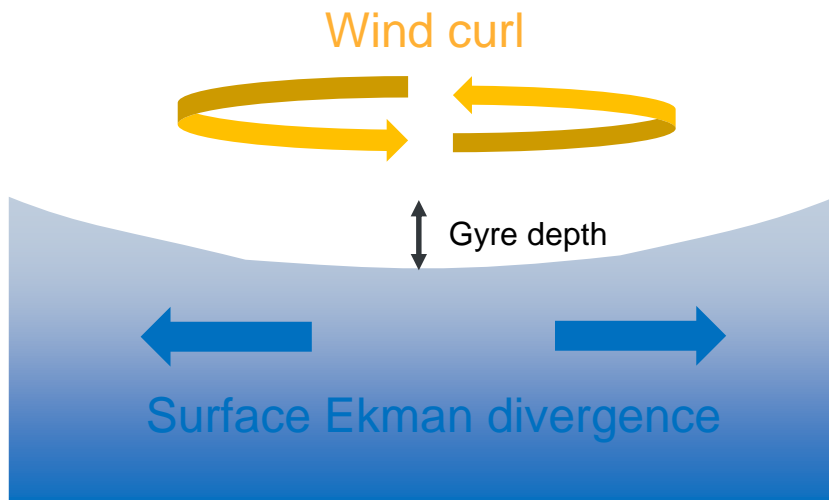
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 - In turn weakly correlated with SAM



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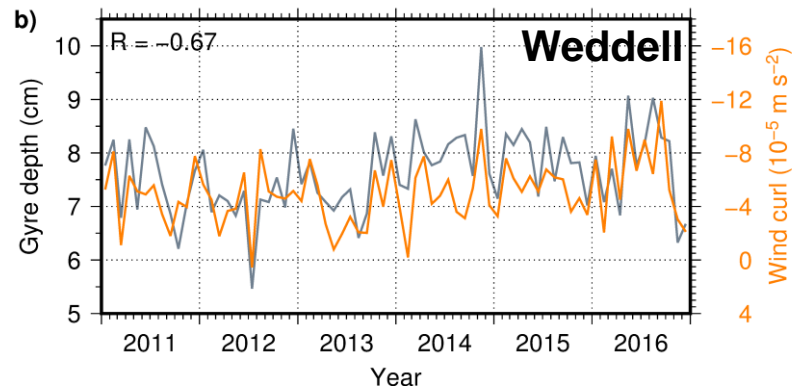
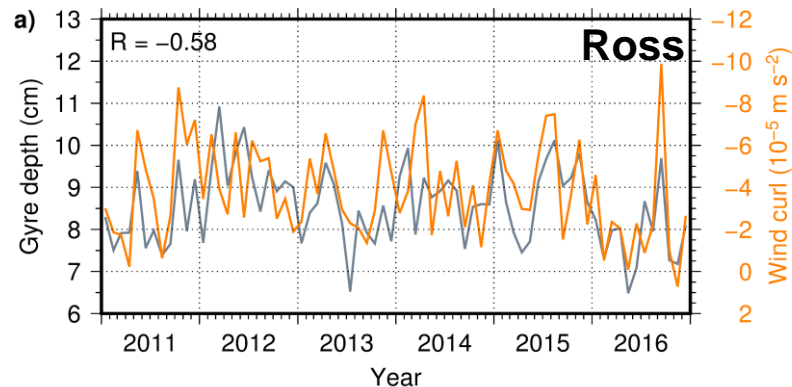
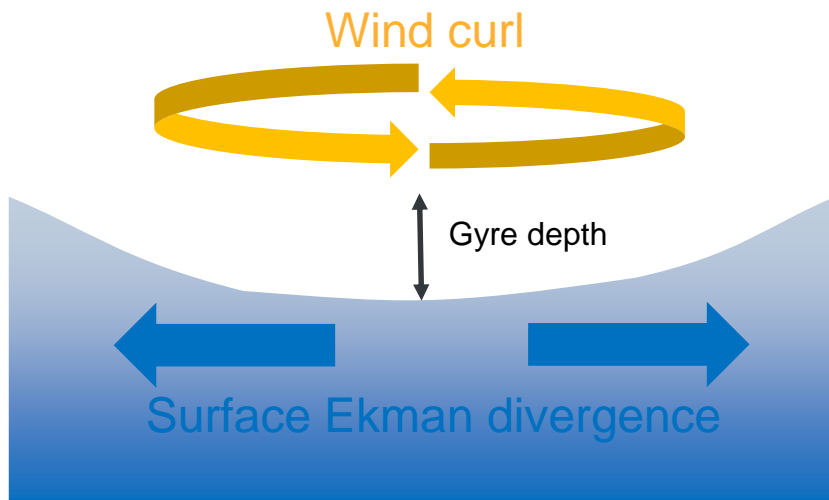
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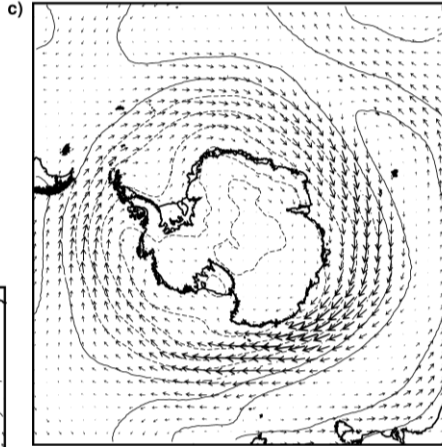
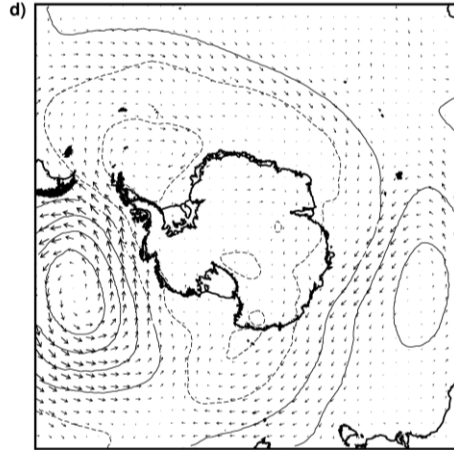
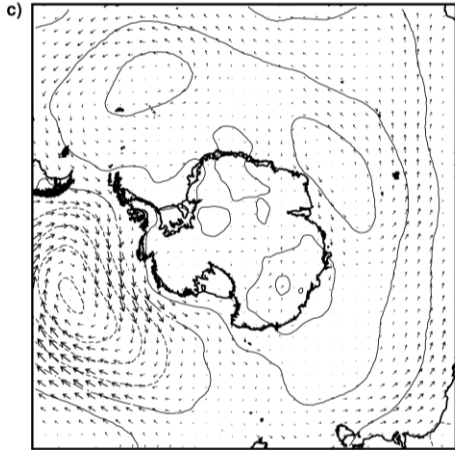
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4. The Southern Ocean – climate variability

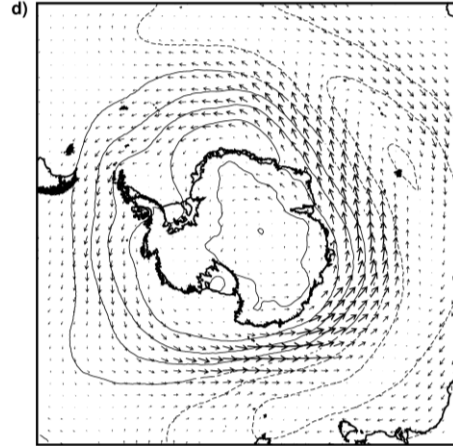
Southern Oscillation
atmospheric signature

SOI+

SOI-



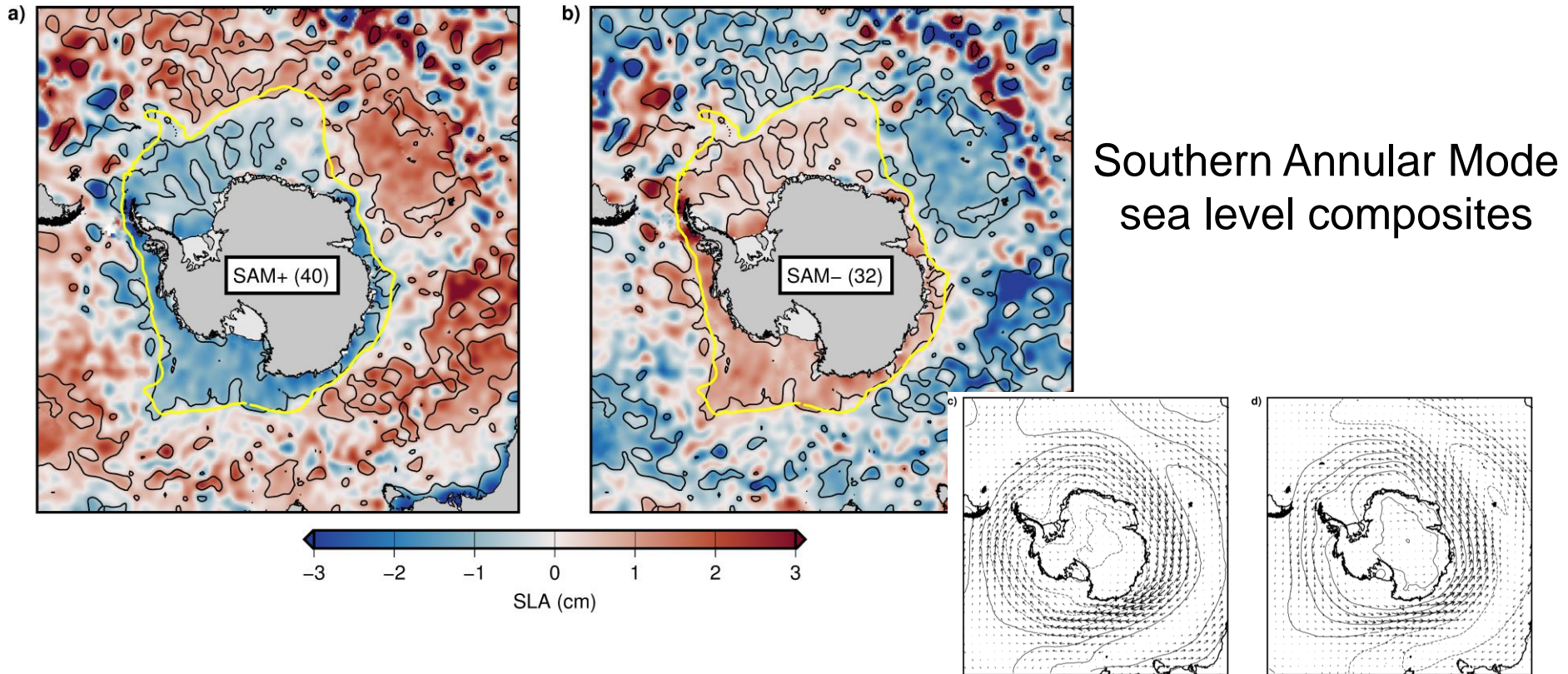
SAM+



SAM-

Southern Annular Mode
atmospheric signature

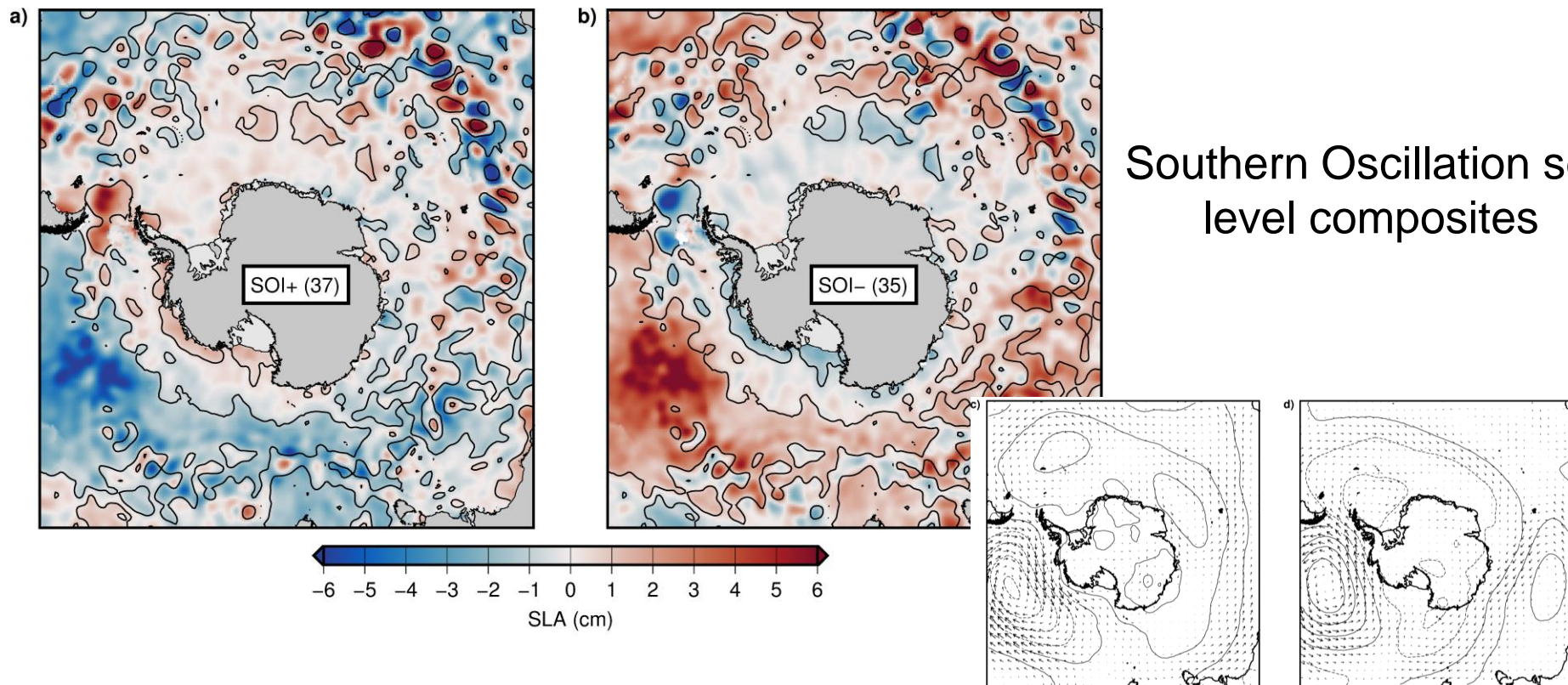
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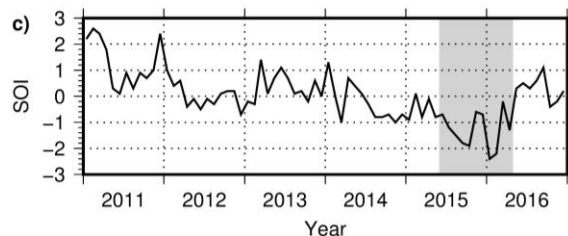
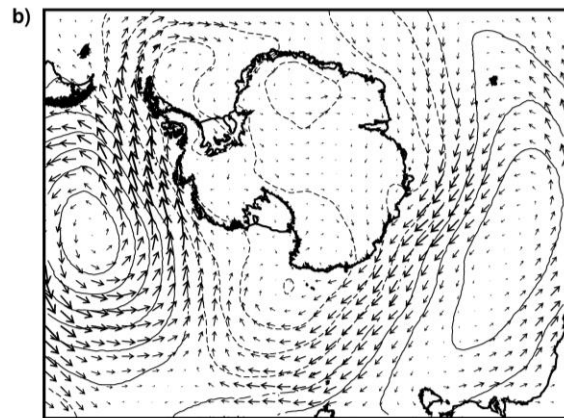
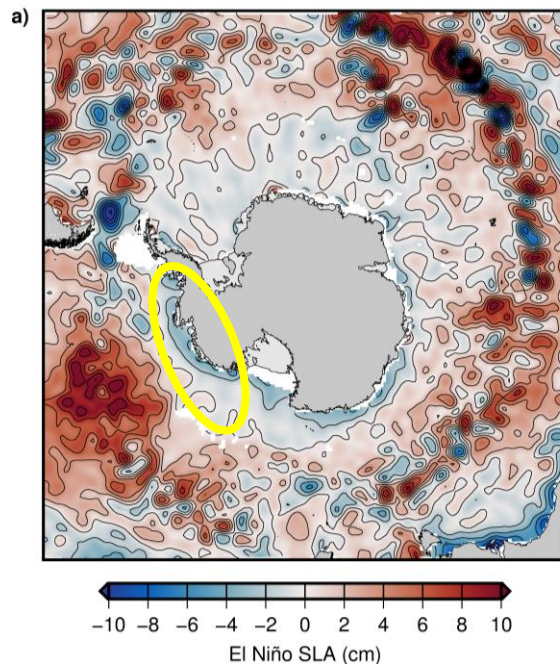
Southern Oscillation sea level composites



Armitage et al. (2018), "Dynamic topography and sea level anomalies of the Southern Ocean: Variability and teleconnections", *JGR-Oceans*, 123.

4. The Southern Ocean – 2015-16 El Niño

- Negative wind-driven coastal sea level anomalies observed off West Antarctica during 2015-16 El Niño event
- What was the sub-surface response?



Armitage et al. (2018), "Dynamic topography and sea level anomalies of the Southern Ocean: Variability and teleconnections", *JGR-Oceans*, 123.

4. The Southern Ocean – 2015-16 El Niño

- Evidence of ice shelf melt rates modulated by ENSO

Figure: Paolo et al. [2018]

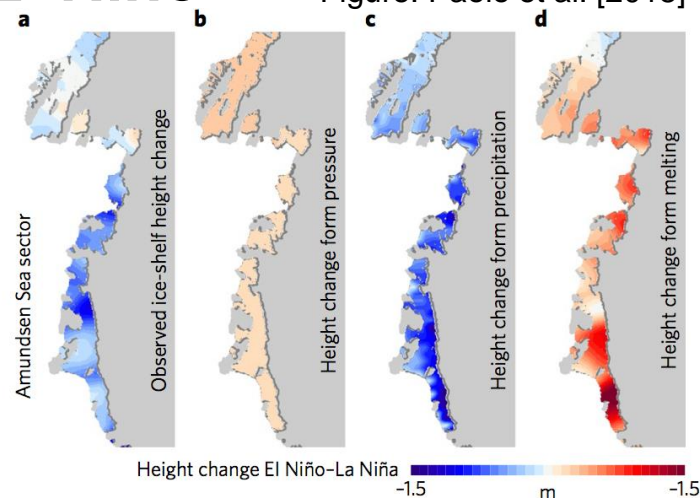
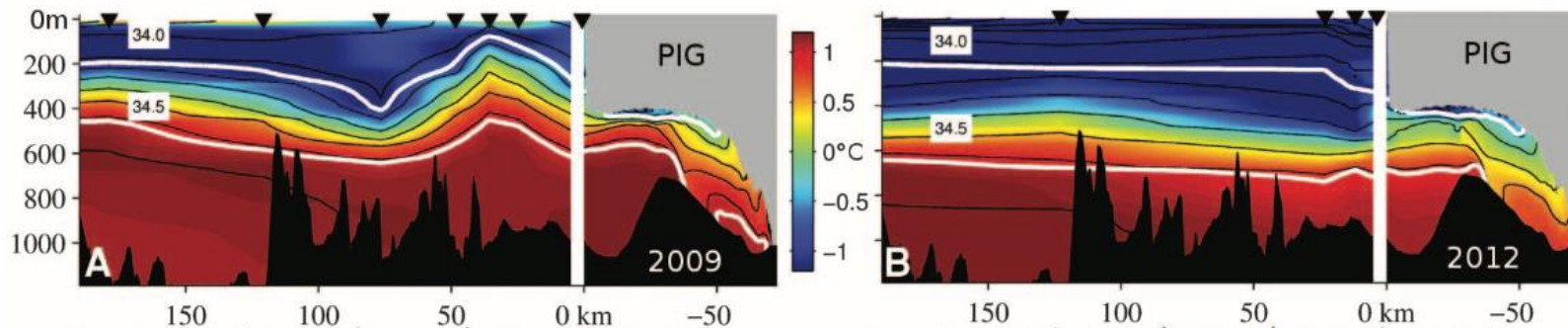


Figure: Dutrieux et al. [2014]



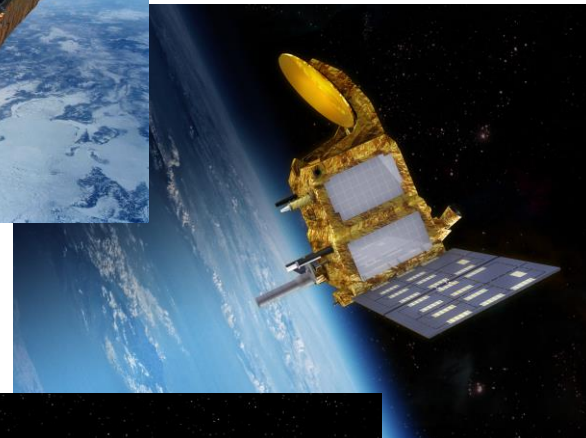
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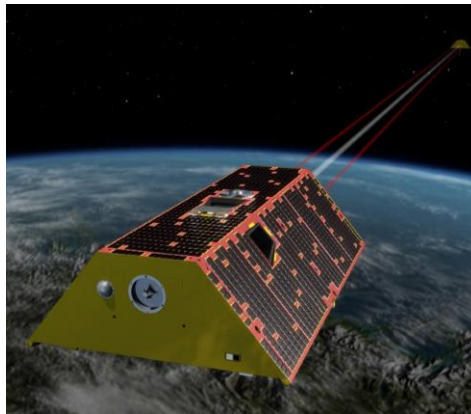
6. Future work

- Extending the data records
- ERS-1/2 back to early-90s
- Never been more altimeters observing the polar oceans
 - CryoSat-2, AltiKa, Sentinel-3a&b
- What is the role of altimeter-derived sea level in an Arctic observing network?
- What are the subsurface changes corresponding to ENSO forcing?



6. Future missions

- GRACE-FO (next week)
 - Continuation of GRACE ocean mass data record
- ICESat-2 (Sept 2018)
 - Laser altimeter; sea ice thickness and DOT
- SWOT (2021)
 - Interferometric radar altimetry; swath height measurements



Conclusions

- Altimetry is great for polar oceanography
 - Data sparse but climatically important ocean regions
- Can produce monthly sea level composites of the ice-covered and ice-free ocean
- Investigated changing freshwater distribution and upper ocean dynamics in the Arctic Ocean
- Reveals monthly to interannual variability in marginal seas of Antarctica, incl. significant ENSO response
- Data coverage can be extended into future, and historically



Sea level and ocean circulation in the ice-covered polar oceans from satellite radar altimetry

Tom Armitage

Supervisor: Ron Kwok

Radar Science and Engineering

Data:

- Arctic Ocean: http://www.cpom.ucl.ac.uk/dynamic_topography/
- Southern Ocean: <https://rkwok.jpl.nasa.gov/cryosat2/>